

AFATL-TR-82-21

20000731152

Ballistic Criteria for Propellant Grain Fracture in the GAU-8/A 30 MM Gun

Reproduced From
Best Available Copy

Clifford W. Fong
Bertram K. Moy

BALLISTICS BRANCH
DIRECT FIRE WEAPONS DIVISION

MARCH 1982

FINAL REPORT FOR PERIOD NOVEMBER 1981-DECEMBER 1981

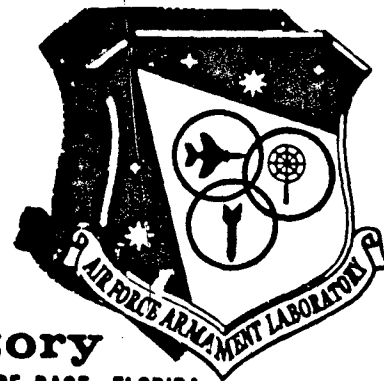
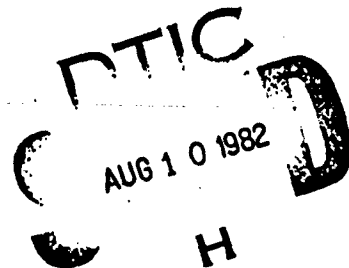
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

Air Force Armament Laboratory
AIR FORCE SYSTEMS COMMAND • UNITED STATES AIR FORCE • EGLIN AIR FORCE BASE, FLORIDA

82 08 10 014

AD A118376

DTIC FILE COPY



NOTICE

**Please do not request copies of this report from the Air Force Armament Laboratory.
Additional copies may be purchased from:**

**National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161**

**Federal Government agencies and their contractors registered with Defense Technical
Information Center should direct requests for copies of this report to:**

**Defense Technical Information Center
Cameron Station
Alexandria, Virginia 22314**

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFATL-TR-82-21	2. GOVT ACCESSION NO. AD-A118 376	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) BALLISTIC CRITERIA FOR PROPELLANT GRAIN FRACTURE IN THE GAU-8/A 30 MM GUN		5. TYPE OF REPORT & PERIOD COVERED Final Report: November 1981-December 1981
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Clifford W. Fong Bertram K. Moy		8. CONTRACT OR GRANT NUMBER(s) In-House
9. PERFORMING ORGANIZATION NAME AND ADDRESS Direct Fire Weapons Division Air Force Armament Laboratory Eglin Air Force Base, Florida 32542		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE: 62602F JON: 2560-08-20
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Armament Laboratory Armament Division Eglin Air Force Base, Florida 32542		12. REPORT DATE March 1982
		13. NUMBER OF PAGES 57
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Availability of this report is specified on verso of front cover.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Propellant grain fracture Temperature sensitivity		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) From plots of V_m^2/P_p (proportional to the piezometric efficiency) versus T derived from multiple GAU-8 gun firings over the temperature range -50°C to +70°C, it is possible to derive criteria for propellant grain fracture during the ballistic cycle. Propellants which do not undergo loss of mechanical integrity show a linear relationship between V_m^2/P_p and T, with negative slopes. In this study it has been found that the single base propellants, CIL		

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. ABSTRACT (CONCLUDED).

3532 and CIL 3331, the current USAF GAU-8/A propellant (GAU-8 extract) and three high performance, cool burning candidate propellants for the GAU-8/A gun (IH .3, IH .5 and ABL 20/21) do not show detectable grain breakup during the ballistic cycle.

Propellants which undergo grain fracture during the ballistic cycle exhibit marked reductions in piezometric efficiencies and consequent deviations from the usual linear relationship between V_m^2/P_p and T. Subambient temperature brittle fracture is usually also accompanied by marked scatter of the V_m^2/P_p values leading to high standard deviation error estimates. Such behavior has been observed in this study for all the triple base propellants Nos. 24, 34, 35, 46, 50/51/52, and 55. However, a triple base propellant (M30 MOD) containing ground nitroguanidine (as opposed to the unground nitroguanidine contained in the other triple base propellants investigated) exhibited a marked improvement in low temperature brittle fracture properties.

Several of the triple base propellants investigated (Nos. 24, 13, 55 and M30 MOD) showed linear regions in their V_m^2/P_p versus T plots (from approximately -10°C to 50°C) which exhibited very low slopes, indicating that the ballistic performance of these propellants was virtually insensitive to temperature change. Such observations are consistent with the postulate that a limited amount of grain fracture is also occurring in this temperature range which offsets the usual decrease of burning rate with decreasing temperature.

At high temperatures (60°C and above) there is evidence that significant grain fracture can occur (No. 55) leading to unusually high P_p (or low V_m^2/P_p) or conversely, that unusually low P_p (or high V_m^2/P_p) can occur (No. 13) by virtue of the fact that grain breakup is not occurring significantly at high temperatures but is occurring at temperatures below 60°C. Such behavior may be reconciled with extensive differential plasticity of the NC binders at high temperatures for these propellants.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

PREFACE

This report documents work performed at the Air Force Armament Laboratory, Armament Division, Eglin Air Force Base, Florida, between November 1981 and December 1981.

Mr. Bertram K. Moy of the Armament Laboratory (DLDL) and Dr. Clifford W. Fong of the Propulsion Division, Weapons Systems Research Laboratory, Defence Research Centre, Salisbury, South Australia were the project engineers for this effort.

The Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service (NTIS), where it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Marvin J. Woodring
MARVIN J. WOODRING, Colonel, USAF
Chief, Direct Fire Weapons Division

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Avail number	
Dist	Special
A	



TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION.	1
II	EXPERIMENTAL.	3
III	DISCUSSION.	5
IV	SUMMARY AND CONCLUSIONS	11
	REFERENCES.	13

LIST OF FIGURES

Figure	Title	Page
1	Muzzle Velocity ² /Peak Pressure versus Temperature for the Single Base Propellant CIL 3532, 140-Gram Charge Weight.	22
2	Muzzle Velocity ² /Peak Pressure versus Temperature for the Single Base Propellant CIL 3331, 140-Gram Charge Weight.	23
3	Muzzle Velocity ² /Peak Pressure versus Temperature for the Double Base Propellant GAU-8 Extract, 148-Gram Charge Weight	24
4	Muzzle Velocity ² /Peak Pressure versus Temperature for the Nitramine Propellant IH .3, 150-Gram Charge Weight.	25
5	Muzzle Velocity ² /Peak Pressure versus Temperature for the Nitramine Propellant ABL 20/21, 137-Gram Charge Weight.	26
6	Muzzle Velocity ² /Peak Pressure versus Temperature for the Nitramine Propellants IH .3 and IH .5, 149-Gram Charge Weight, Showing the Effect of Deterrent/Inhibitor Concentration	27
7	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant No. 24, 140-Gram Charge Weight.	28
8	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant No. 35, 148-Gram Charge Weight.	29
9	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant No. 46, 140-Gram Charge Weight.	30
10	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant No. 50/51/52, 138-Gram Charge Weight.	31
11	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant No. 55, 145- and 155-Gram Charge Weight	32
12	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant No. 13, 142-Gram Charge Weight.	33
13	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant No. 34, 148-Gram Charge Weight.	34
14	Muzzle Velocity ² /Peak Pressure versus Temperature for the Triple Base Propellant M30 MOD, 155-Gram Charge Weight	35
15	Muzzle Velocity ² /Peak Pressure versus Charge Weight for the Double Base Propellant GAU-8 Extract.	36
16	Muzzle Velocity ² /Peak Pressure versus Charge Weight for the Nitramine Propellant IH .3.	37

LIST OF FIGURES (CONCLUDED)

Figure	Title	Page
17	Muzzle Velocity ² /Peak Pressure versus Charge Weight for the Triple Base Propellant No. 55.	38
18	Muzzle Velocity ² /Peak Pressure versus Charge Weight for the Triple Base Propellant No. 13.	39
19	Muzzle Velocity ² /Peak Pressure versus Charge Weight for the Triple Base Propellant No. 34.	40
20	Muzzle Velocity ² /Peak Pressure versus Charge Weight for M30 MOD Propellant	41
21	Scanning Electron Micrographs of the Fracture Surface of the Triple Base Propellant No. 55 (Magnification X600)	42
22	Scanning Electron Micrographs of the Fracture Surface of the Triple Base Propellant No. 13 (Magnification X600)	43
23	Scanning Electron Micrographs of the Fracture Surfaces of the Triple Base Propellant M30 MOD (Magnification X600).	44
24	Pressure -- Time Traces for the Single Base Propellant CIL 3331, at 70°, 20°, and -40°C	45
25	Pressure -- Time Traces for the Double Base Propellant GAU-8 Extract, at 70°, 20°, and -40°C.	46
26	Pressure -- Time Traces for the Nitramine Propellant, IH .3, at 60°, 20°, and -40°C	47
27	Pressure -- Time Traces for the Triple Base Propellant No. 35, at 60°, 20°, and -40°C	48
28	Pressure -- Time Traces for the Triple Base Propellant M30 MOD, at 60°, 20°, and -40°C.	49

LIST OF TABLES

Table	Title	Page
1	Composition and Grain Dimensions for Single Base, Double Base and Nitramine Propellants for GAU-8/A Application.	15
2	Composition and Grain Dimensions for Triple Base Propellants for GAU-8/A Application.	16
3	Ballistic Parameters for Variable Temperature GAU-8/A Firings of CIL 3331 Propellant	17
4	Ballistic Parameters for Variable Temperature GAU-8/A Firings of GAU-8 Extract Propellant.	18
5	Ballistic Parameters for Variable Temperature GAU-8/A Firings of Nitramine (IH .3) Propellant.	19
6	Ballistic Parameters for Variable Temperature GAU-8/A Firings of Triple Base (No. 50/S1/52) Propellant	20
7	Ballistic Parameters for Variable Temperature GAU-8/A Firings of Triple Base (M30 MOD) Propellant.	21

SECTION I

INTRODUCTION

Classical models of the gun interior ballistic cycle have paid scant attention to propellant mechanical properties, generally assuming that individual grains retain their structural integrity during combustion. The assumptions of uniform ignition of the entire propellant bed and simplified gas pressure gradients ignore aspects of propellant bed rheology which may give rise to excessive longitudinal pressure waves. Localized base ignition of the propellant bed can lead to the formation of large longitudinal pressure waves which may accelerate propellant grains forward to impact the projectile base resulting in grain fracture and additional exposed burning surface. The resultant phenomena of bed compaction with accompanying grain fracture may lead to high local pressure levels and pressurization rates. Pressure dependent transient burning effects can then result in very large amplified pressure waves and subsequent peak pressure levels.

To date, there have been few studies of the relationship between pressure waves and ballistic performance and their relationship with catastrophic breech blows. Such studies have been limited to large caliber howitzers (References 1, 2, and 3). Several attempts have been made to theoretically evaluate the role of propellant grain fracture in breech blows (References 4 and 5). A pressure vessel has been built for the evaluation of gun propellants for breech blow hazards (Reference 6).

Gun propellants have been shown to display an increasing propensity towards brittle fracture at high impact velocities and low temperatures (References 7-14) as indicated by a variety of data from laboratory impact testers (References 7-12) and results from closed vessels firings (References 13 and 14). However, to the present time, there has been no systematic investigations of the structural integrity of propellants during the ballistic cycle despite isolated qualitative reports of abnormally high pressures during low temperature firings of some small arms ammunition (Reference 15 and 16).

This study investigates gun firings in the GAU-8 30 mm Mann barrel over the temperature range from -50°C to $+70^{\circ}\text{C}$ for a variety of single base, double base, triple base and nitramine propellants. Triple base propellant such as M30 has been shown to have a history of low temperature grain fracture problems (References 7, 8, 10-12) and appear to display a greater propensity towards brittle fracture than single or double base gun propellants. It has been suggested that this behavior arises from the high proportion of solid oxidizer particles in triple base propellants and that all highly solids loaded propellants (such as the new generation of cool burning nitramine propellants developed by the USAF) may eventually suffer from structural integrity problems during the ballistic cycle unless proper care is taken with formulation parameters as well as particle size and shape. This forecast is based upon the expectation that highly solids loaded propellants contain less nitrocellulose (NC) binder than single base or double base propellants, and consequently possess a higher proportion of crack propagation sites (at the binder--solid oxidizer interface). Similarly, it may be envisaged that the shape of the solid oxidizer will govern the number of possible crack propagation sites, as spheroidal type fillers present fewer crack propagation sites than long irregular needle type fillers (Reference 7).

Moy (References 17 and 18) has suggested that triple base propellants containing ground nitroguanidine (NQ) exhibits superior low temperature ballistic behavior over similar propellants containing unground NQ. Since unground NQ is known to consist of long needle-like crystals, it is expected that ground NQ will contain less needle-like crystals and consequently will have greater mechanical strength by virtue of a reduced number of crack propagation sites.

SECTION II

EXPERIMENTAL

All gun firings were made in a GAU-8 30 mm single shot Mann barrel at Eglin Air Force Base utilizing 375-gram, 389-gram, or 428-gram Aerojet 30 mm GAU-8A projectiles with plastic rotating bands and 30 mm GAU-8/A aluminum cartridge cases. The ignition system was comprised of a M36 or M52 primer with a WECOM 30 flashtube containing 0.35 gram of Class 4 black powder (for the single base CIL* 3532 and CIL 3331 propellants) plus 0.5 - 0.75 gram of boron/potassium nitrate (added as a powder) for some of the propellants used in this study. All rounds were temperature conditioned for a minimum of 48 hours and fired as soon as possible after being removed from the environmental chamber. In the majority of cases, uncrimped rounds were used; however, occasionally crimped rounds were used, which usually resulted in slightly higher P_p (peak pressures) and V_m (muzzle velocities). For some firings, different barrels were used.

The data obtained for Figures 1-14 were averages of multiple firings (usually 5 or greater) and the displayed error bars are +1 Standard Deviation (SD). The data obtained for Figures 15-19 were the average of 3 shots. Some variable temperature firings of single base and triple base propellants were taken from previous AFATL/DLDL records.

The propellant compositions and geometries are given in Tables 1 and 2. The triple base propellants given in Table 2 were manufactured at Radford Army Ammunition Plant, while M30 MOD was manufactured at Indian Head (IH) Naval Ordnance Station (NOS). The nitramine propellants IH .3 and IH .5 were also manufactured at Indian Head NOS, while propellant ABL 20/21 was manufactured at Allegany Ballistics Laboratory (ABL).

*CIL - Canadian Industries, Ltd.

SECTION III

DISCUSSION

It has been observed that low temperature (subambient) 30 mm gun firings at Eglin AFB, Florida and elsewhere (References 15 and 16) have occasionally resulted in anomalously high peak chamber pressures, P_p . Similarly some propellants showed usually low P_p values at higher temperatures (approximately 50° - 60°C) when compared to P_p values obtained at ambient temperatures (for example, M30 propellant). New experimental and production scale propellant batches are often rejected on such criteria. It has often been postulated (References 1-14) that low temperature brittle fracture is responsible for the high P_p values at subambient conditions, but the occurrence of low P_p values at high temperature has been most puzzling.

A systematic gun firing program was carried out in order to elucidate these problems and to establish criteria for the maintenance of propellant structural integrity during the ballistic cycle over a wide temperature range. The propellants which were evaluated included: (a) two single base propellants (CIL 3532 and CIL 3331), (b) a double base propellant* (the current USAF propellant for the GAU-8/A 30 mm cannon), (c) three nitramine propellants (IH .3, IH .5, and ABL 20/21), and eight triple base propellants (M30 type, lot nos, 13, 24, 34, 35, 46, 50/51/52, 55 and M30 MOD).

For a particular propellant, multiple firings (usually at least five) of temperature conditioned rounds were conducted using the same ballistic configuration (i.e. barrel, ignition system, cartridge cases and projectiles) on the same or occasionally the following day. Maximum care was taken to ensure that the ballistic conditions were as similar as possible. Daily calibration of pressure gauges and parallel firings of reference and comparison rounds were carried out to identify and minimize drift of the Kistler pressure gauges.

The variable temperature gun firings for the propellants studied are shown as plots of muzzle velocity $^2 (V_m)^2$ / peak pressure (P_p) versus temperature (T). The term V_m^2/P_p , which is proportional to the piezometric efficiency for a constant ballistic configuration, was used rather than simply P_p , since the piezometric efficiency is a more meaningful indication of ballistic conditions. However, it should be noted that plots of P_p versus T show the same trends as our normal plots, which will be discussed later in detail. Typically, the various propellants, when fired over the temperature range of +70°/+60°C to -40°/-50°C showed a gradual decrease in P_p and V_m with a corresponding increase in the action time (t_a) (see tables 3-7 for some representative ballistic results).

*GAU-8 extract is the propellant extracted from GAU-8 30-mm target practice rounds for inhouse evaluation.

Figures 1 and 2 show plots of V_m^2/P_p versus T for two single base propellants, CIL 3532 and CIL 3331, both with a charge weight (CW) of 140 grams. The error estimates for each point are shown as one standard deviation (SD) calculated for the eight- and ten-shot replicates for CIL 3532 and CIL 3331 respectively. Least squares regression analysis indicate satisfactory linear relationships ($r=0.951$, $n=8$ and $r=0.963$, $n=8$ for CIL 3532 and CIL 3331 respectively). The negative slopes for the V_m^2/P_p versus T plots result from the expected relationship between temperature and burning rate, as well as a contribution from the web size of the propellant grains. A decrease in temperature will correspondingly decrease the enthalpy of combustion, thereby lowering the burning rate and hence the peak pressure and muzzle velocity (Reference 9).

Figure 3 shows a similar plot for GAU-8 extract propellant, at a CW of 148 grams. Again a satisfactory linear relationship between V_m^2/P_p and T is observed ($r=0.970$, $n=13$).

Figures 4 and 5 show plots of two nitramine propellants, IH .3 and ABL 20/21 at CW of 150 grams and 137 grams. Again good linear relationships between V_m^2/P_p and T are observed ($r=0.944$, $n=8$, and $r=0.977$, $n=8$ respectively). The large differences in the slopes (-0.27 compared to -0.60) presumably arise from the different ratios of TACN/HMX in the propellants as well as the different web sizes (Table 1). Figure 6 shows plots for propellants IH .3 and IH .5 (CW of 149 grams), where the only differences in the propellants are the deterrent/inhibitor levels. As expected, two approximately parallel lines are observed with slopes of -0.29 and -0.32 respectively. The data for Figures 4 and 6 were collected approximately a year apart, and were obtained with different weight projectiles (428-gram Aerojet, uncrimped and 389-gram Aerojet, crimped). The observed slope of -0.27 and $-0.29/-0.32$ are in good agreement and indicate that an experimental error of ± 10 percent in the slope can be obtained.

From the data discussed so far, it appears as if the normal dependency between piezometric efficiency and temperature for single base, double base and nitramine propellants in the GAU-8 is a linear relationship. The sensitivity of the piezometric efficiency to temperature for a constant charge weight is a function of the burning rate, propellant composition and/or web size.

However, the triple base propellants (M30 type) show drastically different behavior from that observed thus far. Figures 7-11, which are plots for triple base propellant batches Nos. 24, 35, 46, 50/51/52 blend and 55, all show drastically different behavior from that observed thus far. Figures 7-11, which are plots for triple base propellant batches Nos. 24, 35, 46, 50/51/52 blend and 55, all show drastically reduced piezometric efficiencies at temperatures from -20°C to -40°C . These reductions in efficiencies are usually accompanied by large increase in scatter of V_m^2/P_p (as indicated by larger Standard Deviations). However, at temperatures above approximately -20°C , all propellants show the usual linear dependence between V_m^2/P_p and T. We believe these data are only consistent with low temperature brittle failure of the triple base propellant.

One further point of interest which arises from Figures 7-10 is the large variation in the slopes of the linear portion of these figures. As the compositions (other than the deterrent/inhibitor concentrations which do not change the slope, see above) and webs are very similar (Table 2), we would expect the slopes to be similar. However, the slopes of the linear regions vary from -0.14 to -0.30 which is outside the range of experimental inaccuracy.

Figure 1. also shows the effect of charge weight on these plots: essentially parallel relationships for CWs of 145 and 155 grams. The slope of the linear portion of the plot is -0.20; i.e., the piezometric efficiency is virtually independent of temperature, a totally unexpected result given the well known variation of burning rate with temperature. The unusually low piezometric efficiencies shown at 60°C will be discussed later. Suffice to say that these points appear real, since the CW of the 145-gram and CW of 155-gram data were collected about a year apart by different experimenters.

Figure 12 similarly shows a linear temperature independent range above 0°C, while grain breakup appears to occur at -10°C and below in triple base propellant No. 13. The slope of the linear portion of the plot is again extremely low.

Figure 13 shows the variable temperature behavior of triple base propellant No. 34 at a CW of 148 grams. With the exception of the point at -20°C, the propellant shows normal behavior, as adjudged by the results for the single base, double base, and nitramine propellants previously discussed. Batch No. 34 appeared to be the only one of the Radford AAP triple base propellant batches evaluated which did not exhibit brittle fracture at low temperatures. It appears that the -20°C point in Figure 13 may simply be experimental scatter, although there is no reason, a priori, to expect that propellant brittleness will simply increase as the temperature decreases.*

Hence, of eight similar batches of triple base propellant investigated in detail, only one batch (No. 34) appears not to undergo subambient brittle fracture in the GAU-8/A gun. However, while these compositional and geometrically similar propellants do show the expected linear behavior of piezometric efficiency with temperature (usually above 0°C) the slopes of the regions vary from virtually zero to approximately -0.36. In view of the known effects of temperature on burning rates of propellants, it can be speculated that the only way a propellant can display a piezometric efficiency which is insensitive to temperature is for another mechanism to be operating in the opposite direction to the known decrease of burning rate with decreasing temperature. A viable and plausible mechanism is a limited amount of grain fracture at temperatures above 0°C. However, at this stage we still have not considered the role of CW, which may cloud our conclusions (see below).

Moy has previously suggested (References 17 and 18) that ground NQ in a triple base formulation can increase the mechanical strength. Figure 14 shows a plot of M30 MOD (modified with respect to the fact that the propellant contains ground NQ instead of "as received" unground NQ) at a CW of 155 grams. It

*The presence of significant primary and secondary loss transitions for cellulosic type polymer systems can confer added fracture toughness in temperature regions where such transitions occur (References 20 and 21).

can be seen that the degree of low temperature brittle fracture (as seen in Figures 7-12) is substantially reduced, with perhaps a small amount of grain fracture at -40°C . Again as for batches No. 55 and No. 13, the linear region of the graph displays a very low slope, indicating ballistic performance is virtually insensitive to temperature effects.

However, as indicated above, the role of CW has not been considered since the data portrayed in Figures 1-14 were obtained with different charge weights. Because of varying web sizes and deterrent levels, the charge weights were varied to obtain approximately the same peak pressures in the gun firings. The role of ullage or free space between the propellant bed and projectile base may complicate simple inferences about propellant structural integrity from our data.

Figure 15 shows a plot of V_m^2/P_p versus CW for GAU-8 extract propellant for a variety of temperatures. A family of approximately parallel lines is observed, regularly decreasing (with respect to interception of the V_m^2/P_p axis) from low temperature to high temperature.

Figure 16 shows a similar plot for a nitramine propellant, IH .3. Again a family of roughly parallel lines is observed, regularly decreasing from -40°C to $+60^{\circ}\text{C}$.

However, in strong contrast to Figures 15 and 16, Figures 17 and 18, which portray data for the triple base propellants No. 55 and No. 13, show no regular progression with respect to temperature. Figure 17 clearly shows the consequences of what we have assumed to be grain fracture at -20°C and -40°C . Firstly, the lines for -20°C and -40°C are substantially displaced towards lower piezometric efficiencies than expected (given a normal burning rate dependency on temperature), and secondly, these lines (which were deliberately drawn as parallel to the higher temperature lines) show marked scatter from a simple linear relationship. Thirdly, the 60°C line is significantly separated from the 20° and 40°C lines.

Figure 18 is even more unusual than Figure 17. The -20°C and -40°C lines lie below the higher temperature lines, indicating excessive grain fracture, but the order of progression for the 0° , 20° , 40° , and 60°C lines is the inverse of the expected order. Also noteworthy is the very low slopes of the temperature lines.

We believe that the data in Figures 17 and 18 is consistent with the hypothesis that while excessive brittle fracture of grains can occur at -20°C to -40°C for triple base propellants, some lesser degree of grain breakup is also occurring at ambient temperatures and above.* The data in Figure 17 indicates propellant No. 55 is showing excessively high peak pressures or low piezometric efficiencies at 60°C (see Figure 11 also). Such data suggests excessive grain breakup at $+60^{\circ}\text{C}$ as well as from -20°C to -40°C . While such a result seems difficult to

*Grain breakup may vary from wholesale shattering of grains into small pieces (e.g. brittle fracture at -40°C) to small cracks (especially at the binder-oxidizer interface) within propellant grains, such as may be occurring at ambient temperatures and above.

reconcile, as previously noted, there is no reason to expect a cellulosic-type polymer to display fracture behavior which is linearly related to temperature (References 20 and 21). In contrast, the data in Figure 18 suggests propellant No. 13 is showing unusually low peak pressures or high piezometric efficiencies at 60°C. The data in Figure 18 suggests that excessive grain fracture is occurring at -20°C to -40°C, and some lesser and diminishing degree of breakup is occurring from 0°C to +40°C. At 60°C then, propellant No. 13 is displaying a low P_p by virtue of the fact that it is not breaking up.

It may well be that the anomalous behavior of propellants No. 55 and No. 13 at temperatures above ambient is associated with plastic deformation of the nitrocellulose (NC) binder (as opposed to brittle elastic failure at -20°C to -40°C). Thus extensive plasticity (on the ductile side of the brittle-ductile transition) coupled with differential uneven binder distribution in No. 55 and No. 13 could account for the different behavior of the propellant at 60°C.

It was suggested earlier that the triple base propellant No. 34 appeared to show no sign of grain breakup at low temperatures (Figure 13). However a plot of V_m^2/P_p versus CW indicates that this initial assessment was incorrect. It can be seen from Figure 19 that grain fracture is occurring at 0°C and below, since the 0°, -20°, and -40°C lines lie below the 20°C line. The data in Figure 19 emphasizes the importance of the V_m^2/P_p versus CW plots (for various temperatures) for determining grain fracture since spurious results can occasionally occur with the simple V_m^2/P_p versus T plots (at a constant charge weight).

Figure 20 shows a plot of V_m^2/P_p versus CW for the triple base propellant M30 MOD. It is noteworthy that this propellant shows a remarkable insensitivity of its performance to temperature change. Some small degree of grain breakup may be occurring at -20° to -40°C, but within experimental error, it may be concluded that the family of parallel lines for the various temperatures are essentially the same line. Certainly, the contrast between Figure 20 and Figure 17 is striking.

As we anticipated in the Introduction, a triple base formulation containing ground NQ should show greater mechanical strength than similar propellants containing unground needle-like NQ. Figures 21, 22, and 23 show scanning electron micrographs of fracture surfaces of triple base propellants No. 55, No. 13 and M30 MOD. Especially in the micrographs of the leached fracture surfaces (H_2O indicates that the NQ was leached out by hot water) it can be seen that M30 MOD shows a much more even NC binder distribution than propellants No. 55 and No. 13. Hence, the less needle-like shape of the NQ crystals and the resultant more even NC distribution confers greater mechanical strength on the M30 MOD propellant.

One aspect of the ballistic data we have so far ignored is the pressure versus time curves for individual shots. Some representative pressure-time traces for a single base, double base, nitramine, triple base and M30 MOD at 60°/70°C, 20°C and -40°C are shown in Figures 24-27 respectively. In all cases, even when substantial grain breakup is occurring, fairly smooth and reproducible

pressure-time traces were observed. This situation is in contrast to the observation of "ragged" pressure-time traces observed for nondeterred propellant in large caliber howitzers. Such traces have been associated with the hydrodynamics of nonuniform ignition leading to large longitudinal pressure waves which are thought to cause grain fracture at the leading edge of the propellant bed (Reference 2). Presumably, the significant drops in piezometric efficiencies observed for the majority of triple base propellants in this study result from only a small proportion of fractured grains at the leading edge of the propellant bed. If this was the case, then coupled with the use of deterred propellant in a 30 mm cartridge case, it may well be that the perturbations caused by grain fracture do not significantly affect the pressure-time traces.

SECTION IV

SUMMARY AND CONCLUSIONS

From plots of V_m^2/P_p (proportional to the piezometric efficiency) versus T derived from multiple GAU-8 gun firings over the temperature range -50°C to $+70^\circ\text{C}$, it is possible to derive criteria for propellant grain fracture during the ballistic cycle. Propellants which do not undergo loss of mechanical integrity show a linear relationship between V_m^2/P_p and T , with negative slopes. In this study it has been found that the single base propellants, CIL 3532 and CIL 5531, the current USAF GAU-8/A propellant (GAU-8 extract) and three high performance, cool burning candidate propellants for the GAU-8/A gun (IH .3, IH .5 and ABL 20/21) do not show detectable grain breakup during the ballistic cycle.

Propellants which undergo grain fracture during the ballistic cycle exhibit marked reductions in piezometric efficiencies and consequent deviations from the usual linear relationship between V_m^2/P_p and T . Subambient temperature brittle fracture is usually also accompanied by marked scatter of the V_m^2/P_p values leading to high standard deviation error estimates. Such behavior has been observed in this study for all the triple base propellants Nos. 24, 34, 46, 50, 51, 52, and 55. However, a triple base propellant (M30 MOD) containing ground nitroguanidine (as opposed to the unground nitroguanidine contained in the other triple base propellants investigated) exhibited a marked improvement in low temperature brittle fracture properties.

Several of the triple base propellants investigated (Nos. 24, 13, 55 and M30 MOD) showed linear regions in their V_m^2/P_p versus T plots (from approximately -10°C to 50°C) which exhibited very low slopes, indicating that the ballistic performance of these propellants was virtually insensitive to temperature change. Such observations are consistent with the postulate that a limited amount of grain fracture is also occurring in this temperature range which offsets the usual decrease of burning rate with decreasing temperature.

At high temperatures (60°C and above) there is evidence that significant grain fracture can occur (No. 55) leading to unusually high P_p (or low V_m^2/P_p) or conversely, that unusually low P_p (or high V_m^2/P_p) can occur (No. 13) by virtue of the fact that grain breakup is not occurring significantly at high temperatures but is occurring at temperatures below 60°C . Such behavior may be reconciled with extensive differential plasticity of the NC binders at high temperatures for these propellants.

The results gained in this study for triple base gun propellants have extensive ramifications for current problems found in the US Army's M30 propellant. Further, our results imply that all triple base propellants may eventually suffer from grain breakup, especially at low temperatures. The shape and size of oxidizer particles have a strong influence on mechanical

strength. The implications are that all highly solids loaded propellants with small binder contents may also suffer from grain breakup unless due consideration is given to formulation parameters as well as particle size and shape. However, this work indicates that it is possible to manufacture highly solids loaded propellants (such as the new generation of cool burning propellants developed by the USAF) which maintain their structural integrity over a wide temperature range.

It is suggested that all new candidate propellants for the GAU-8 and other small caliber gun systems be scrutinized for possible grain breakup by multiple firings over a wide temperature range. Plots of V_m^2/P_p versus T (at constant charge weights) are sufficient for quick checks of mechanical integrity, but plots of V_m^2/P_p versus CW (for varying temperatures) are required for full characterization. The important criteria to characterize mechanical behavior during the ballistic cycle are deviations from linear behavior (low V_m^2/P_p values) with accompanying large increases in scatter (SD) and the slope of the linear relationship between V_m^2/P_p and CW (or T).

Such ballistic criteria of grain fracture should then be correlated with actual laboratory tests of propellant mechanical strength, such as fracture toughness estimates from impact tests or interrupted closed vessel tests (Reference 7).

REFERENCES

1. Clarke, E. V. and May, I. W., "Subtle Effects of Low-Amplitude Pressure Wave Dynamics on the Ballistic Performance of Guns," 11th JANNAF Combustion Meeting, Vol 1, CPIA Publication 261, pp. 141-156, December 1974.
2. Horst, A. W., May, I. W., and Clarke, E. V., "The Missing Link Between Pressure Waves and Breechblows," ARBRL-MR-01849, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1978.
3. Olenick, P. J., "Investigation of the 76MM/62 Caliber Mark 75 Gun Mount Malfunction," NSWC/DL TR-3144, Naval Surface Weapons Center, Dahlgren, VA, October 1975.
4. Fisher, E. B., "Continuing Investigation of Breechblow Physics," 16th JANNAF Combustion Meeting, Vol 1, Naval Postgraduate School, Monterey, CA, pp. 631-651, September 1979.
5. Horst, A. W., "The Role of Mechanical Properties in Propelling Charge Phenomenology," 18th JANNAF Structure and Mechanical Behavior Subcommittee Meeting, Pasadena, CA, December 1981.
6. Hershkowitz, J. and Velicky, R. W., 16th JANNAF Combustion Meeting, Vol 1, Naval Postgraduate School, Monterey, CA, pp. 547-558, September 1979.
7. Fong, C. W., "Mechanical Properties of Gun Propellants - An Assessment of Possible Approaches to Laboratory Testing," Weapons Systems Research Laboratory, Defence Research Centre Salisbury, South Australia, WSRL-0120-TM, December 1979.
8. Fong, C. W. and Stevens, W., "A Subsonic Gas Gun for Pneumatic Projection of Gun Propellant Grains," Weapons Systems Research Laboratory, Defence Research Centre Salisbury, South Australia, WSRL-0000-TM, 1981.
9. Lieb, R. J., Rocchio, J. J. and Koszoru, A. A., "Impact Mechanical Properties Tester for Gun Propellants," 18th JANNAF Structure and Mechanical Behavior Subcommittee Meeting, Pasadena, CA, December 1981.
10. Nicolaidis, S., Weigand, D. A. and Pinto, J., "The Mechanical Behavior of Gun Propellant Grains and Its Role in Interior Ballistics," 16th JANNAF Structure and Mechanical Behavior Subcommittee Meeting, CPIA Publication 311, Vol 1, 1980.
11. Schubert, H. and Schmitt, D., "Embrittlement of Gun Powder," Proceedings on the International Symposium on Gun Propellants, Picatinny Arsenal, Dover, NJ, October 1973.
12. Benhaim, P., Paulin J. and Zeller, B., "Investigation of Gun Propellant Break-up and Its Effect in Interior Ballistics," 4th International Symposium on Ballistics, Monterey, CA, October 1978.
13. Russell, K. H. and Goldstein, H. M., "Investigation and Screening of M-17 Propellant Production for Lots Subject to Poor Low Temperature Performance," DB-TR-7-61, Picatinny Arsenal, Dover, NJ, June 1961.

14. Davies, D. G., Holt, R. B. and Carter, R. E., "Effect of Physical Properties, Composition and Processing on the Break-up of Gun Propellant Charges," TTCP Technical Panel W-4 Meeting, Quebec City, Canada, July 1981.
15. Zeigler, H. and Mellow, D., Hercules Inc. Kenvil, NJ, personal communication.
16. Heiney, O.K., AFATL/DLDL, Eglin Air Force Base, FL, personal communication.
17. Moy, B. K., "Modification of Nitroguanidine for Gun Propellant Applications," JANNAF Propulsion Meeting, CPIA Publication 340, Vol III, pp. 375-388, New Orleans, LA, May 1981.
18. Moy, B. K., "Characterization of Nitroguanidine for Use in Gun Propellants," Ballistics Branch, Direct Fire Weapons Division, Air Force Armament Laboratory, Eglin Air Force Base, FL, AFATL-TR-80-11, January 1980.
19. Corner, J., "Theory of the Interior Ballistics of Guns," John Wiley, New York, NY, 1950, Ch. 4.
20. Fong, C. W., "Dynamic Mechanical Properties of Gun Propellants -- The Relationship Between Impact Fracture Properties and Secondary Loss Transitions," Weapons Systems Research Laboratory, Defence Research Centre Salisbury, South Australia, WSRL-0204-TR, 1981.
21. Fong, C. W., "The Effect of Temperature and Strain Rate on the Impact Fracture Toughness of Plastic Q and the Relationship with Dynamic Mechanical Loss Transitions," Weapons Systems Research Laboratory, Defence Research Centre Salisbury, South Australia, WSRL-0202-TM, February 1981; also presented at the TTCP Technical Panel W-4 Meeting, Quebec City, Quebec, July 1981.

TABLE 1. COMPOSITION AND GRAIN DIMENSIONS FOR SINGLE BASE, DOUBLE BASE
AND NITRAMINE PROPELLANTS FOR GAU-8/A APPLICATION

Propellant Ingredients	CIL 3532	CIL 3331	GAU-8 Extract	IH .3	IH .5	ABL 20/21
NC (12.6N)	95.4	95.4	82.3	20.0	20.0	19.3
NG	----	----	9.4	----	----	----
Plasticizer	----	----	4.3	4.8	4.8	5.0
TAGN (4-5 μ)	----	----	----	45.0	45.0	50.3
HMX (4-5 μ)	----	----	----	29.5	29.5	24.3
Additives	2.1	2.1	1.3	0.7	0.7	0.7
Deterrent						
MC	2.6	2.6	----	----	----	----
G-54	----	----	3.0	0.3	0.45	0.40
Perforations	1	1	1	7	7	7
Length, in	0.086	0.081	0.080	0.242	0.242	0.18
Diameter, in	0.071	0.066	0.077	0.212	0.212	0.175
Avg Web, in	0.032	0.029	0.035	0.046	0.046	0.034

NC - Nitrocellulose

NG - Nitroglycerine

TAGN - Triaminoguanidine Nitrate

HMX - Sym-Tetramethylene Tetranitramine

MC - Methylcentralite

G-54 - Rohm and Haas Proprietary Polyester Resin

TABLE 2. COMPOSITION AND GRAIN DIMENSIONS FOR TRIPLE BASE
PROPELLANTS FOR GAU-8/A APPLICATION

Propellant Composition

NC - 29.62 ± 1.76
NG - 18.76 ± 0.64
NQ - 49.92 ± 1.74
EC - 1.52 ± 0.12
K₂SO₄ - 0.78 ± 0.28

Batch	Deterrent	Length, in	Diameter, in	Avg Web, in
13	1.5 EC	0.148	0.112	0.020
24	1.25 EC	0.147	0.123	0.020
34	1.50 G-54	0.146	0.132	0.023
35	1.7 EC	0.148	0.130	0.022
46	1.0 G-54	0.129	0.129	0.019
50	0.48 G-54	0.131	0.134	0.019
51	0.71 G-54	0.131	0.134	0.019
52	0.86 G-54	0.131	0.134	0.019
55	1.14 G-54	0.132	0.128	0.018
M-30 MOD	0.20 G-54	0.170	0.151	0.027

NOTE: (1) M-30 MOD propellant contained ground NQ, all others contained "as received" NQ
(2) All propellants had 7 perforations

NQ - Nitroguanidine
EC - Ethyl Centralite
K₂SO₄ - Potassium Sulfate

TABLE 3. BALLISTIC PARAMETERS FOR VARIABLE TEMPERATURE
GAU-8/A FIRINGS OF CIL 3331 PROPELLANT

TEMP (°C)	P _p (Kpsi)	V _m (ft/sec)	Action Time (msec)	V _m ² /P _p (ft/sec) ² /psi
70	60.3 (1.4)	3142 (18)	4.9 (0.2)	163.8 (3.5)
55	57.0 (2.0)	3117 (20)	4.9 (0.2)	170.7 (4.9)
40	57.3 (2.1)	3104 (21)	5.2 (0.3)	168.4 (6.2)
20	55.5 (1.5)	3092 (22)	5.4 (0.2)	172.1 (5.3)
5	52.1 (1.6)	3058 (14)	5.7 (0.2)	179.7 (6.2)
-10	49.0 (1.6)	3025 (23)	6.2 (0.5)	186.7 (4.3)
-30	48.0 (1.2)	3000 (11)	6.2 (0.2)	187.8 (5.1)
-40	48.1 (2.0)	2985 (20)	6.8 (0.4)	185.8 (2.8)

NOTES:

1. Average of 10 shots
2. Value in parenthesis is one standard deviation
3. Charge Weight 140 grams; crimped 428 gram Aerojet projectile
4. Flashtube ignitor

TABLE 4. BALLISTIC PARAMETERS FOR VARIABLE TEMPERATURE
GAU-8/A FIRINGS OF GAU-8 EXTRACT PROPELLANT

TEMP (°C)	P _p (Kpsi)	V _m (ft/sec)	ACTION TIME (msec)	V_m^2/P_p (ft/sec) ² /psi
70	52.1 (0.9)	3116 (16)	5.1 (0.7)	186.5 (4.6)
60	51.4 (0.8)	3102 (11)	5.1 (0.5)	187.3 (3.9)
50	52.2 (0.6)	3118 (7)	5.5 (0.1)	186.2 (1.7)
40	51.2 (0.6)	3106 (6)	5.7 (0.1)	183.5 (1.8)
30	51.3 (2.3)	3144 (8)	5.3 (0.1)	192.7 (3.4)
20	52.3 (2.3)	3153 (27)	5.8 (0.1)	190.4 (5.4)
10	49.3 (1.4)	3103 (15)	5.7 (0.4)	195.3 (3.7)
0	47.3 (0.8)	3074 (14)	6.0 (0.1)	199.8 (1.9)
-10	45.6 (0.7)	3053 (13)	6.3 (0.2)	204.5 (3.1)
-20	47.8 (1.1)	3068 (15)	7.2 (0.3)	206.4 (7.1)
-30	45.2 (0.9)	3070 (29)	7.5 (0.3)	208.4 (3.0)
-40	44.2 (1.0)	3043 (7)	7.3 (0.2)	209.3 (1.3)
-50	43.2 (2.2)	3018 (26)	7.6 (0.4)	211.1 (7.2)

NOTES:

1. Average of 5 shots
2. Value in parenthesis is one standard deviation
3. Charge weight 148 grams; uncrimped 428 gram Aerojet projectile
4. Flashtube ignitor + 0.5 gram B/KNO₃

TABLE 5. BALLISTIC PARAMETERS FOR VARIABLE TEMPERATURE
GAU-8/A FIRINGS OF NITRAMINE (1H .3) PROPELLANT

TEMP (°C)	P _p (Kpsi)	V _m (ft/sec)	ACTION TIME (msec)	V_m^2/P_p (ft/sec) ² /psi
80	72.7	3544	4.3	172.8
60	65.9 (1.5)	3587 (59)	4.6 (0.6)	195.3 (8.8)
40	59.2 (3.3)	3484 (24)	5.5 (0.5)	205.4 (10.1)
20	55.2 (3.6)	3401 (39)	5.5 (0.5)	210.2 (9.2)
0	52.9 (4.5)	3325 (38)	5.6 (0.4)	209.9 (13.0)
-20	45.3 (2.0)	3184 (34)	6.4 (0.3)	223.7 (5.4)
-40	43.4 (2.4)	3117 (26)	6.4 (0.6)	224.3 (9.0)

NOTES:

1. Average of 5 shots; 80°C 1 shot only
2. Value in parenthesis is one standard deviation
3. Charge weight 149 grams; crimped 389 gram Aerojet projectile
4. Flashtube ignitor + 0.5 grams B/KNO₃

TABLE 6. BALLISTIC PARAMETERS FOR VARIABLE TEMPERATURE GAU-8/A
FIRINGS OF TRIPLE BASE (NO. 50/51/52) PROPELLANT

TEMP (°C)	P _p (Kpsi)	V _m (ft/sec)	ACTION TIME (msec)	V _m ² /P _p (ft/sec) ² /psi
70	59.4 (1.3)	3186 (30)	4.7 (0.3)	170.9 (3.4)
60	54.3 (1.2)	3137 (27)	4.9 (0.6)	181.7 (2.8)
50	53.0 (0.4)	3140 (7)	5.5 (0.7)	186.1 (2.9)
40	51.6 (0.9)	3122 (18)	6.0 (0.4)	188.9 (1.8)
30	53.0 (0.8)	3135 (12)	5.5 (0.5)	185.6 (3.5)
20	48.7 (0.5)	3083 (8)	6.0 (0.4)	195.0 (2.0)
10	51.3 (1.0)	3114 (19)	5.4 (0.2)	189.1 (2.7)
0	44.9 (1.5)	2983 (23)	6.3 (0.4)	198.3 (3.9)
-10	45.8 (2.6)	2985 (29)	6.7 (1.2)	194.7 (7.0)
-20	43.3 (2.4)	3012 (113)	8.3 (0.7)	206.4 (7.1)
-30	52.7 (5.6)	2961 (65)	7.7 (0.6)	167.2 (20.8)
-40	47.3 (4.0)	2967 (38)	7.6 (0.7)	187.9 (9.8)
-50	53.2 (8.4)	2992 (47)	7.6 (0.7)	171.1 (21.4)

NOTES:

1. Average of 5 shots
2. Value in parenthesis is one standard deviation
3. Charge weight 138 grams; uncrimped 428 gram Aerojet projectile
4. Flashtube ignitor + 0.5 gram B/KNO₃

TABLE 7. BALLISTIC PARAMETERS FOR VARIABLE TEMPERATURE GAU-8/A
FIRINGS OF TRIPLE BASE (M30 MOD) PROPELLANT

TEMP (°C)	P _p (Kpsi)	V _m (ft/sec)	ACTION TIME (msec)	V_m^2/P_p (ft/sec) ² /psi
60	53.3 (1.5)	3074 (30)	5.9 (0.3)	177.4 (2.1)
40	49.1 (1.3)	3029 (11)	6.4 (0.3)	187.1 (3.8)
20	49.8 (2.5)	3000 (24)	6.2 (0.1)	181.1 (6.8)
0	45.9 (1.2)	2917 (9)	7.3 (0.7)	185.5 (4.7)
-10	47.6 (2.7)	2924 (18)	6.8 (0.4)	179.9 (8.3)
-20	46.2 (1.4)	2935 (18)	6.3 (0.1)	186.4 (3.2)
-30	45.4 (2.9)	2907 (28)	6.4 (0.2)	186.5 (8.5)
-40	48.0 (0.2)	2914 (32)	6.6 (0.1)	176.9 (3.9)

NOTES:

1. Average of 5 shots
2. Value in parenthesis is one standard deviation
3. Charge weight 155 grams; uncrimped 428 gram Aerojet projectile
4. Flashtube ignitor + 0.75 gram B/KNO₃

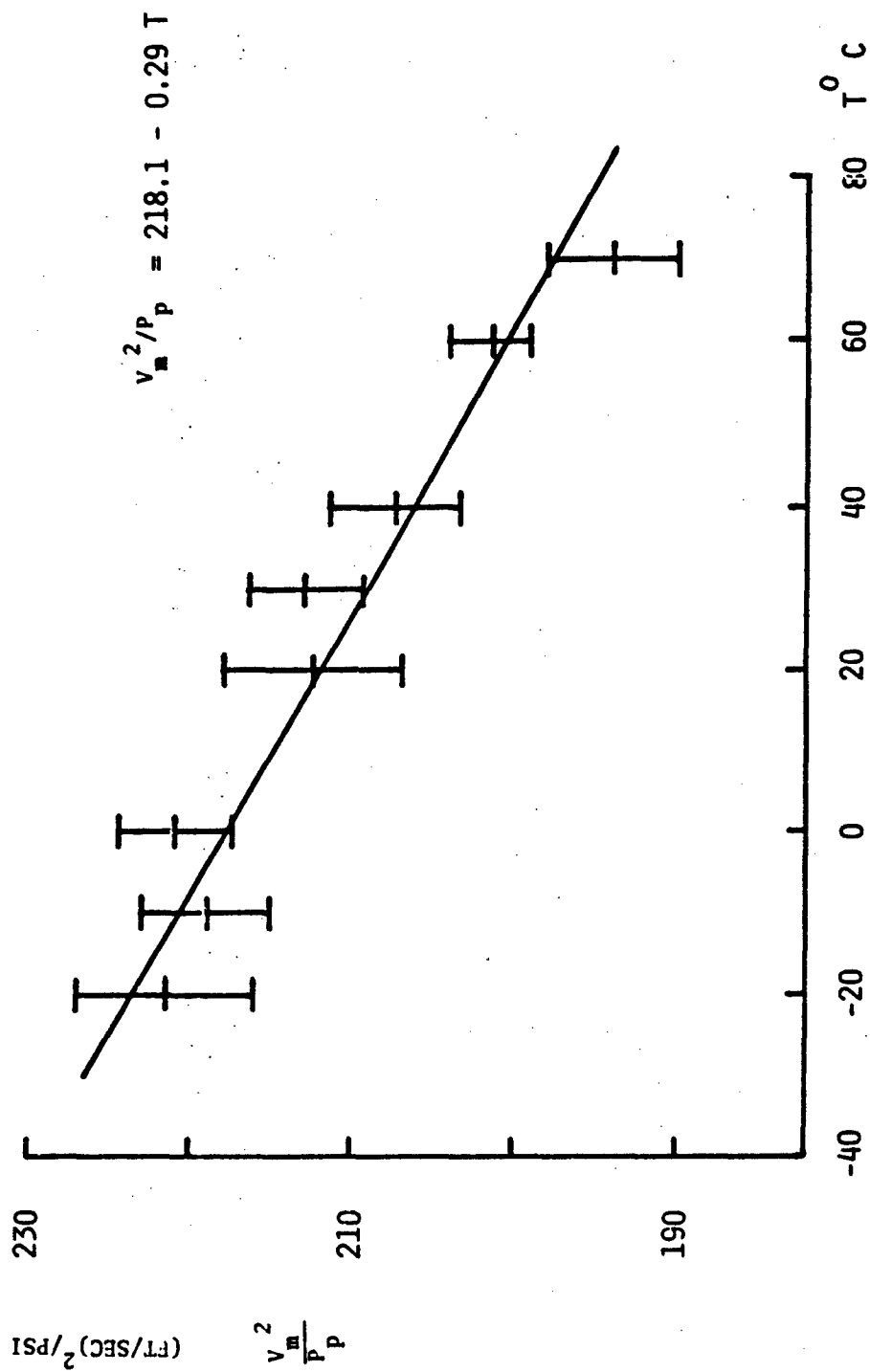


Figure 1. Muzzle Velocity²/Peak Pressure versus Temperature for the Single Base-Propellant CIL-3532, 140-Gram Charge Weight

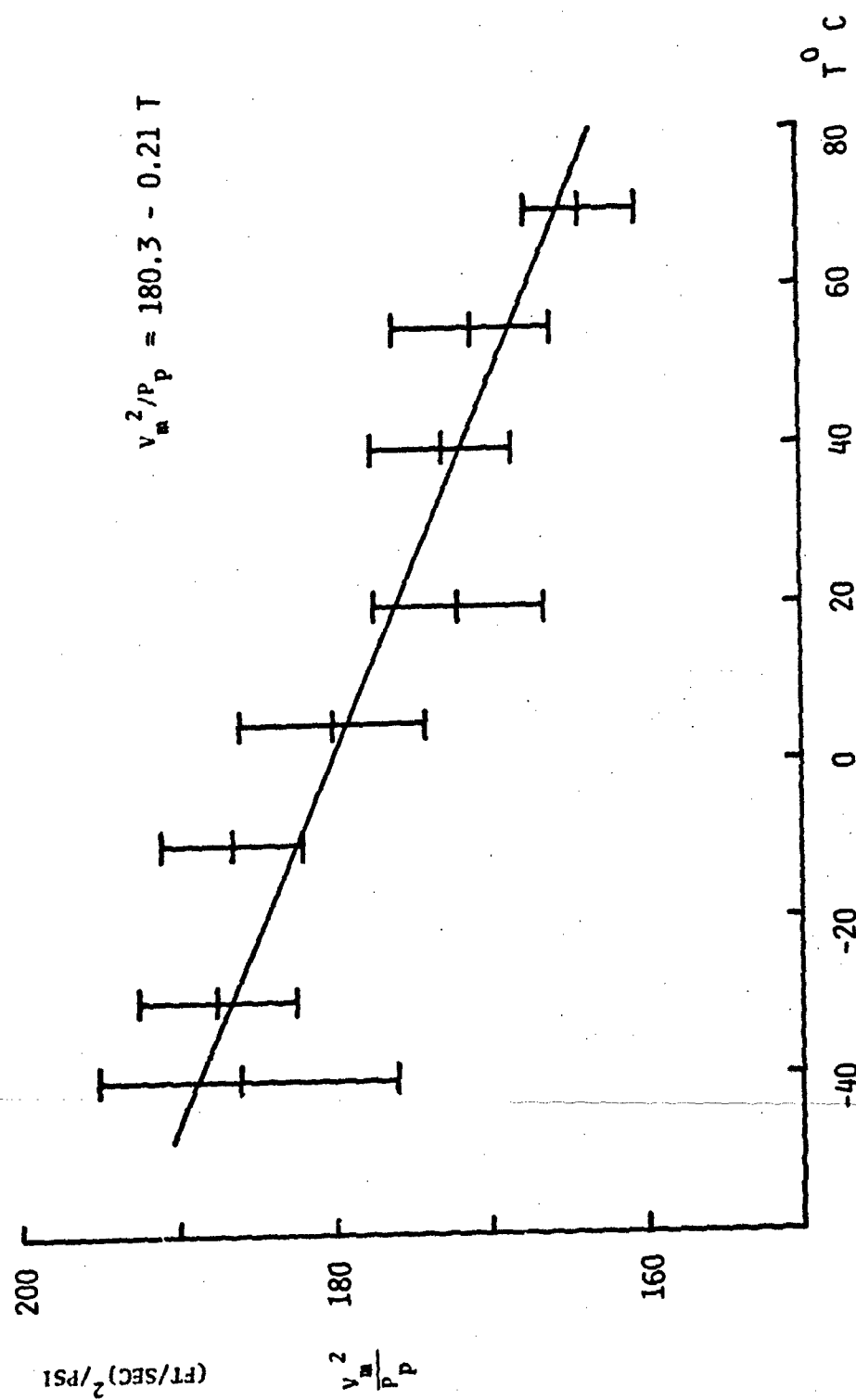


Figure 2. Muzzle Velocity²/Peak Pressure versus Temperature for the Single Base Propellant CIL 3331, 140-Gram Charge Weight

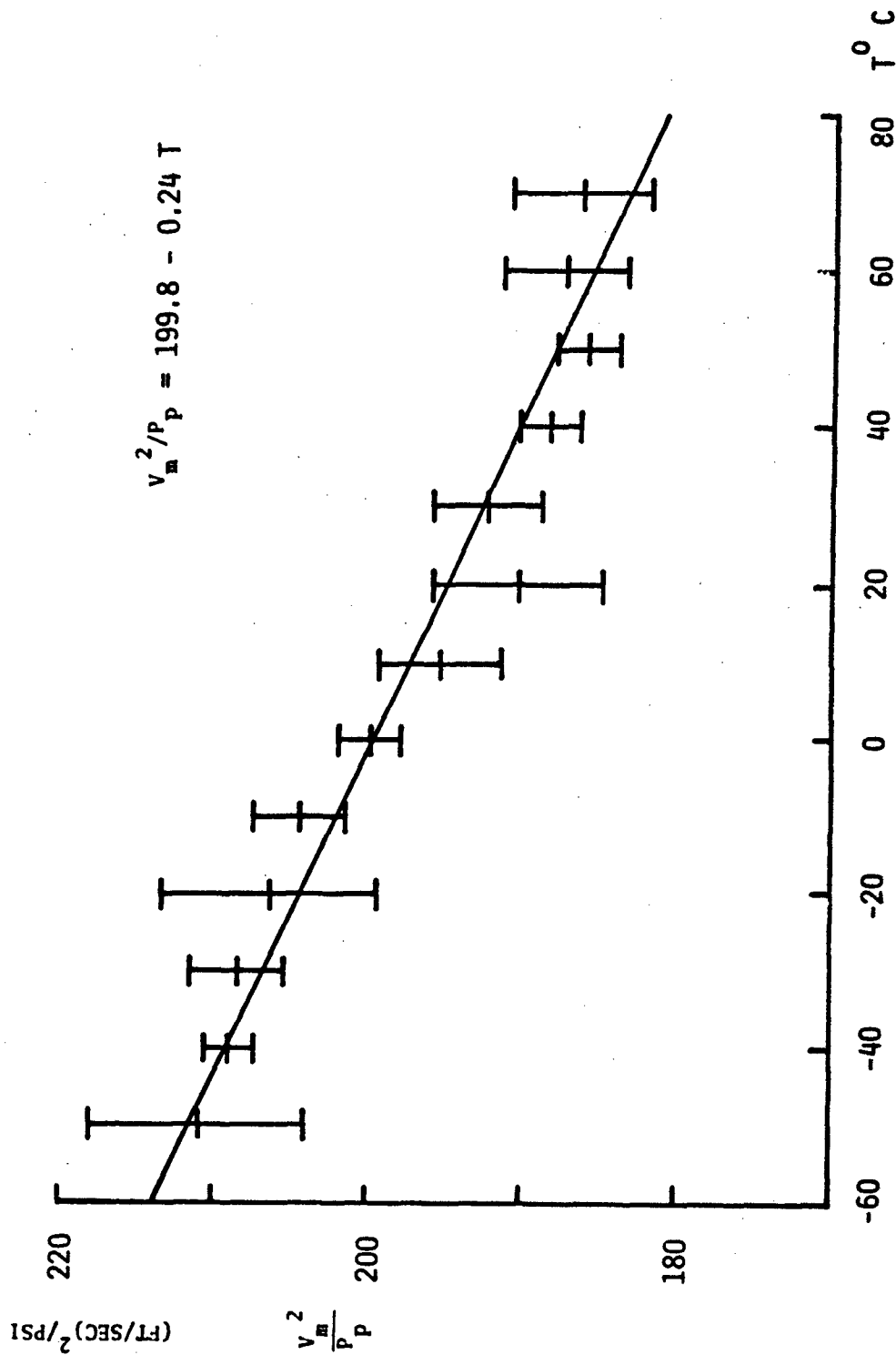


Figure 3. Muzzle Velocity²/Peak Pressure versus Temperature for the Double Base Propellant GAU-8 Extract, 148-Gram Charge Weight

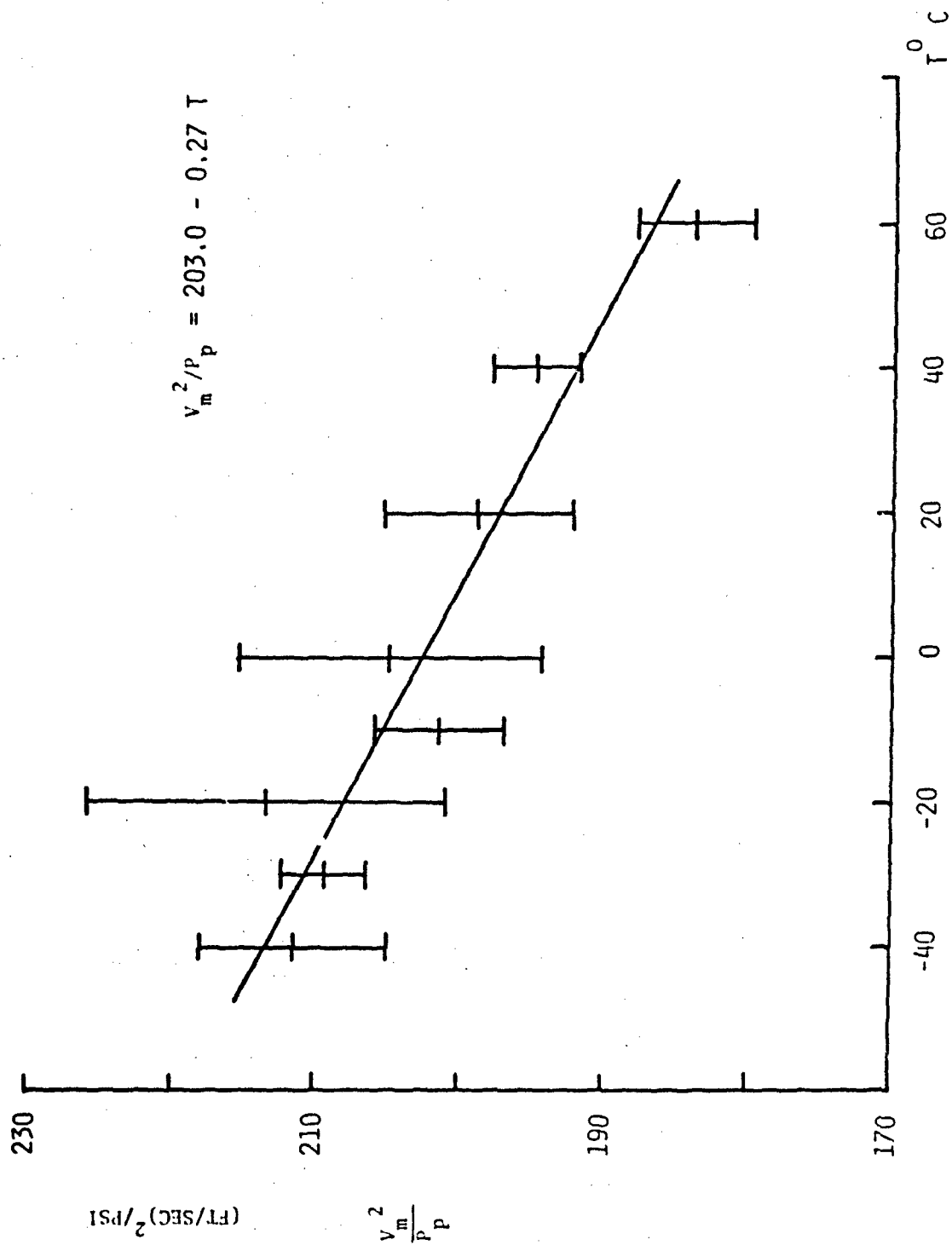


Figure 4. Muzzle Velocity²/Peak Pressure versus Temperature for the Nitramine Propellant III .3, 150-Gram Charge Weight

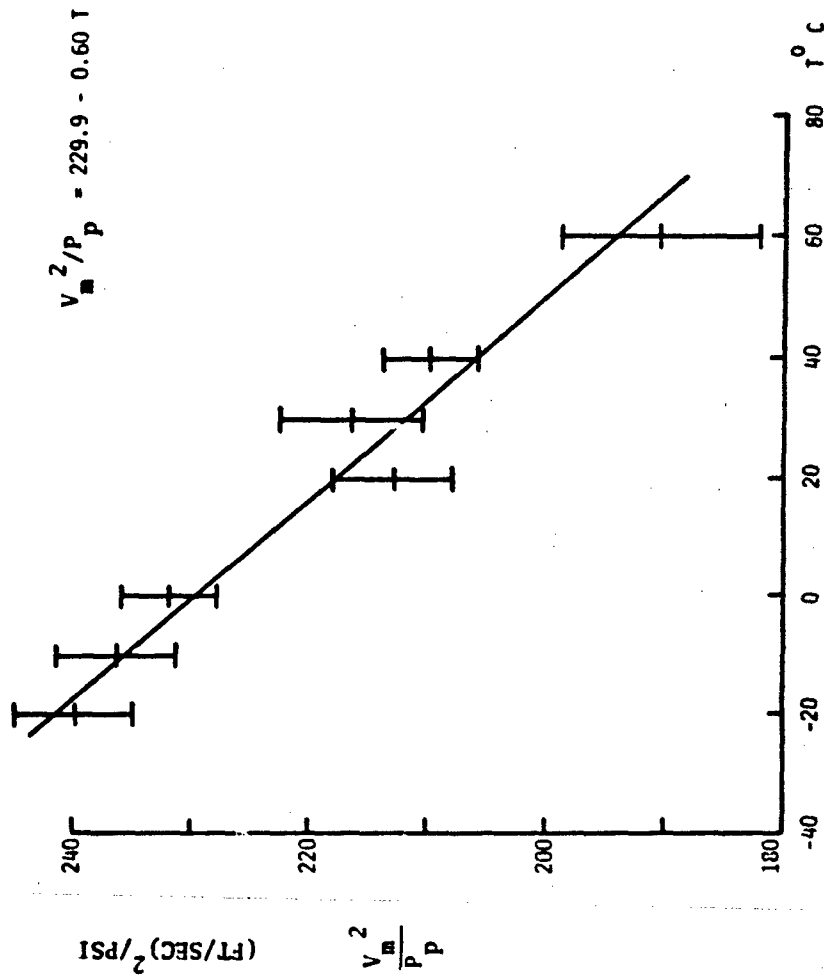


Figure 5. Muzzle Velocity²/Peak Pressure versus Temperature for the Nitramine Propellant ABL 20/21, 137-Gram Charge Weight

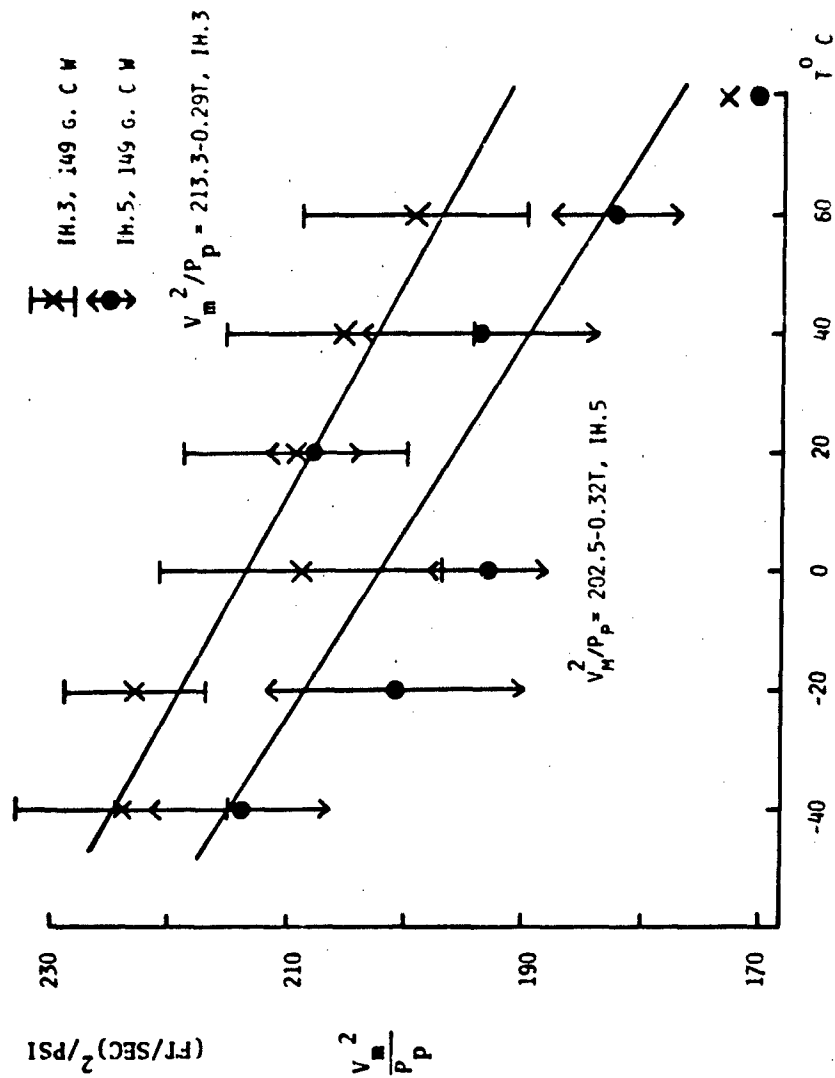


Figure 6. Muzzle Velocity²/Peak Pressure versus Temperature for the Nitramine Propellants IH .3 and IH .5, 149-Gram Charge Weight, Showing the Effect of Deterrent/Inhibitor Concentration

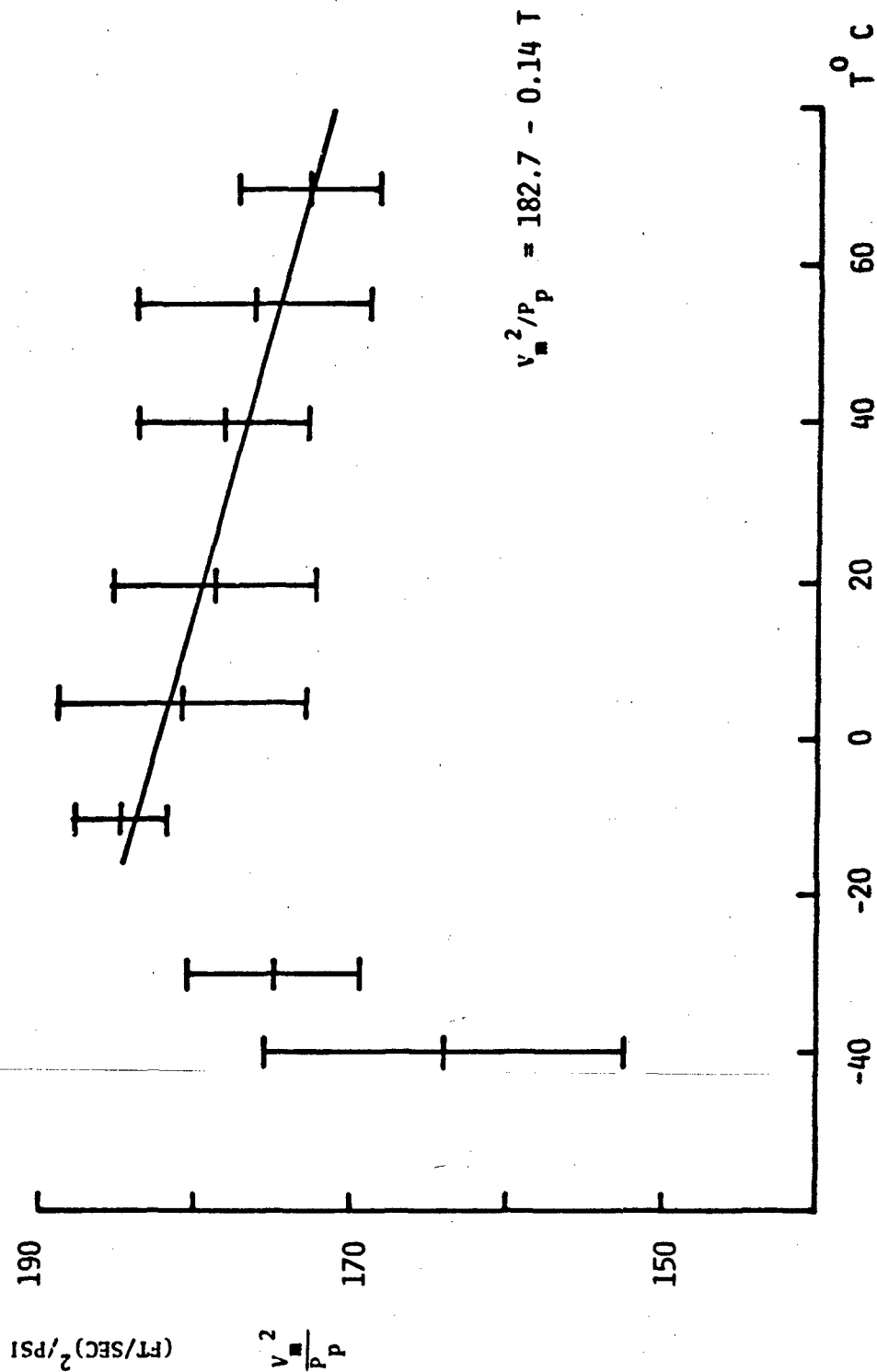


Figure 7. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant No. 24, 140-Gram Charge Weight

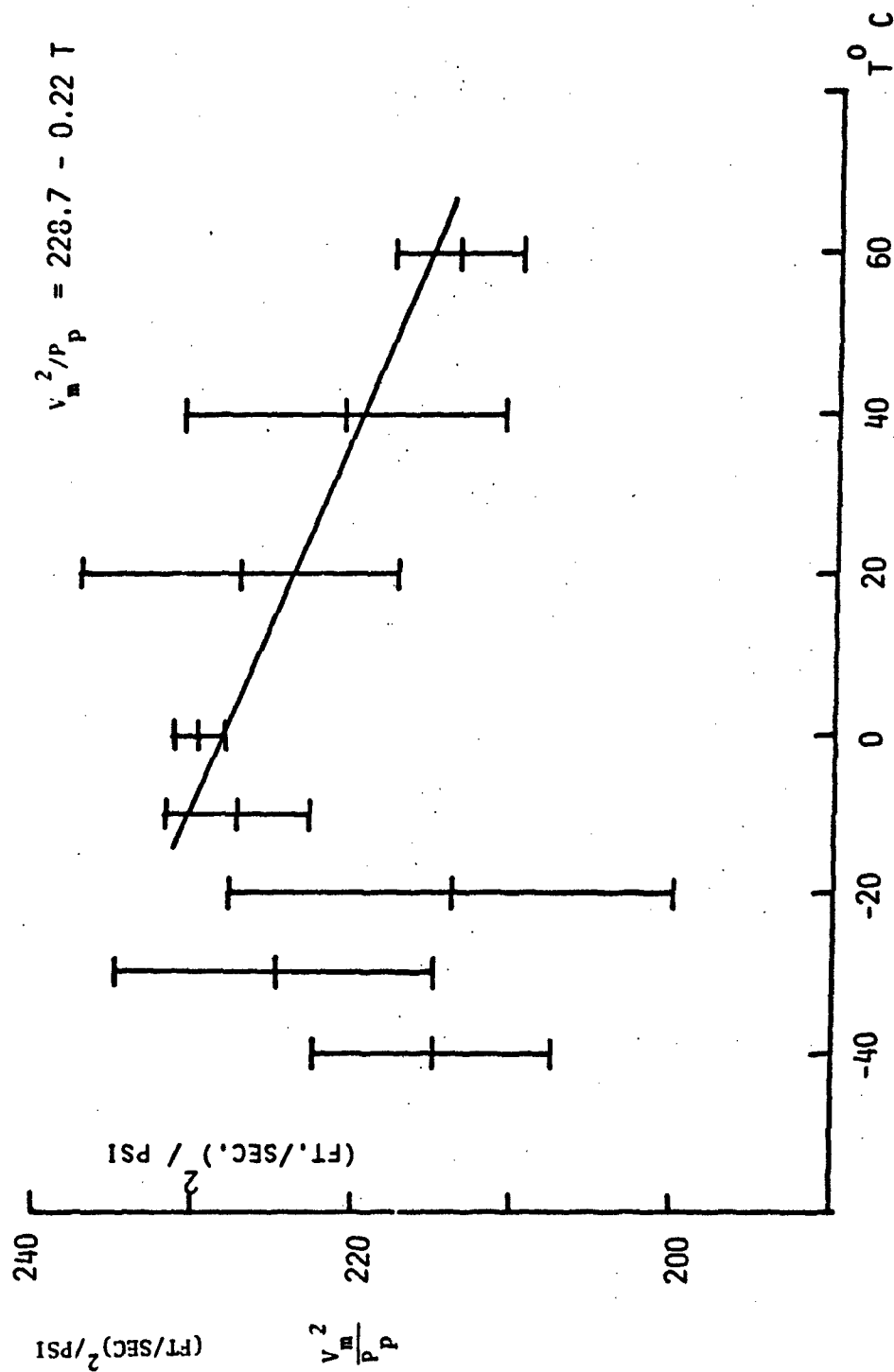


Figure 8. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant No. 35, 148-Gram Charge Weight

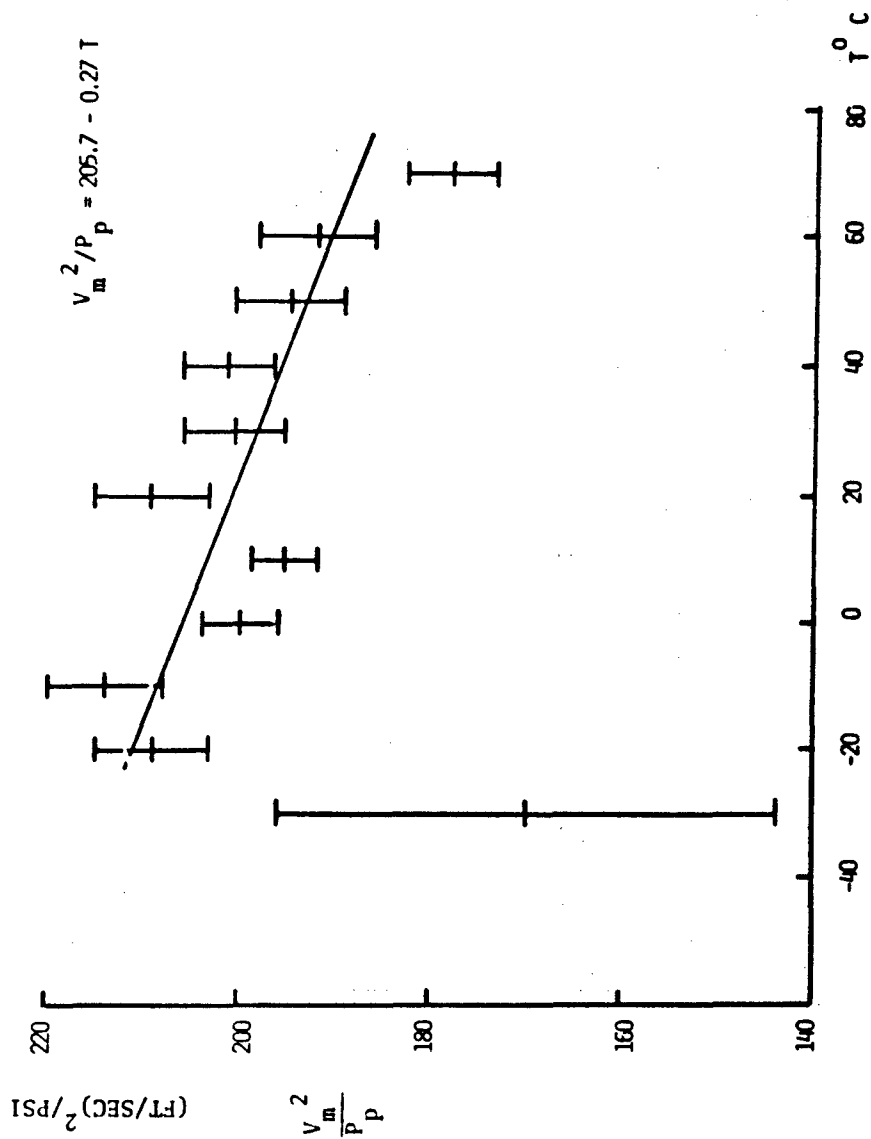


Figure 9. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant No. 46, 140-Gram Charge Weight

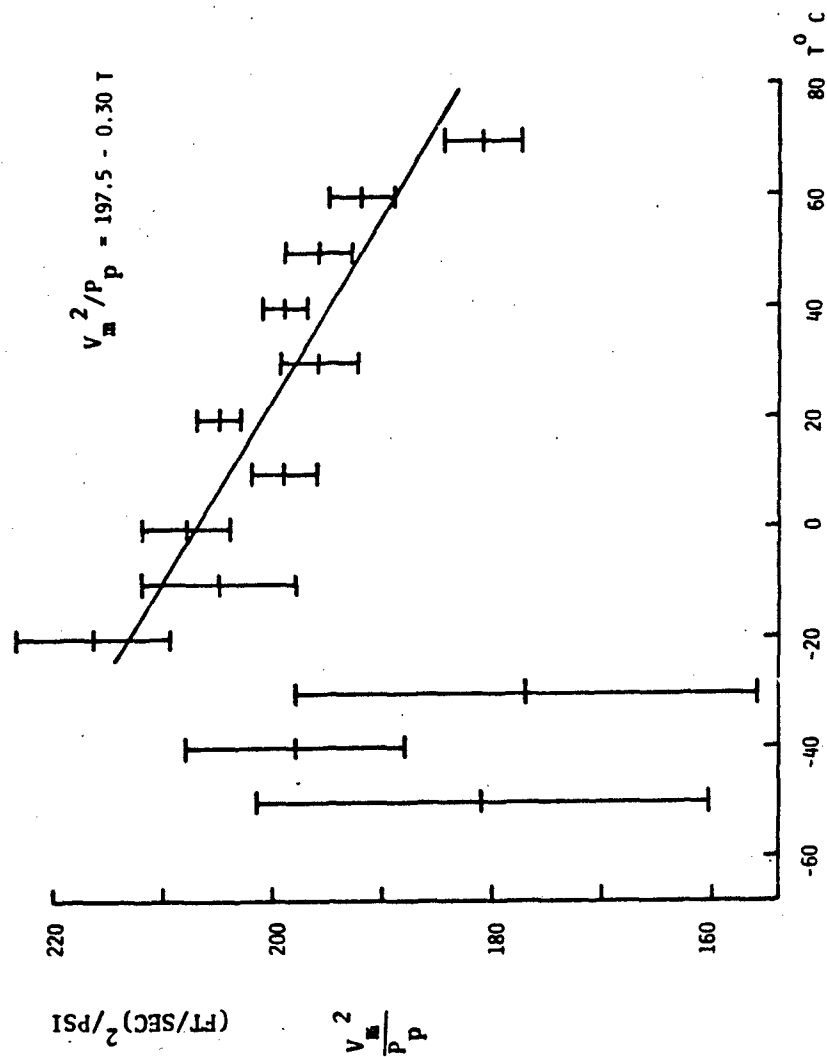


Figure 10. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant No. 59/51/52, 138-Gram Charge Weight

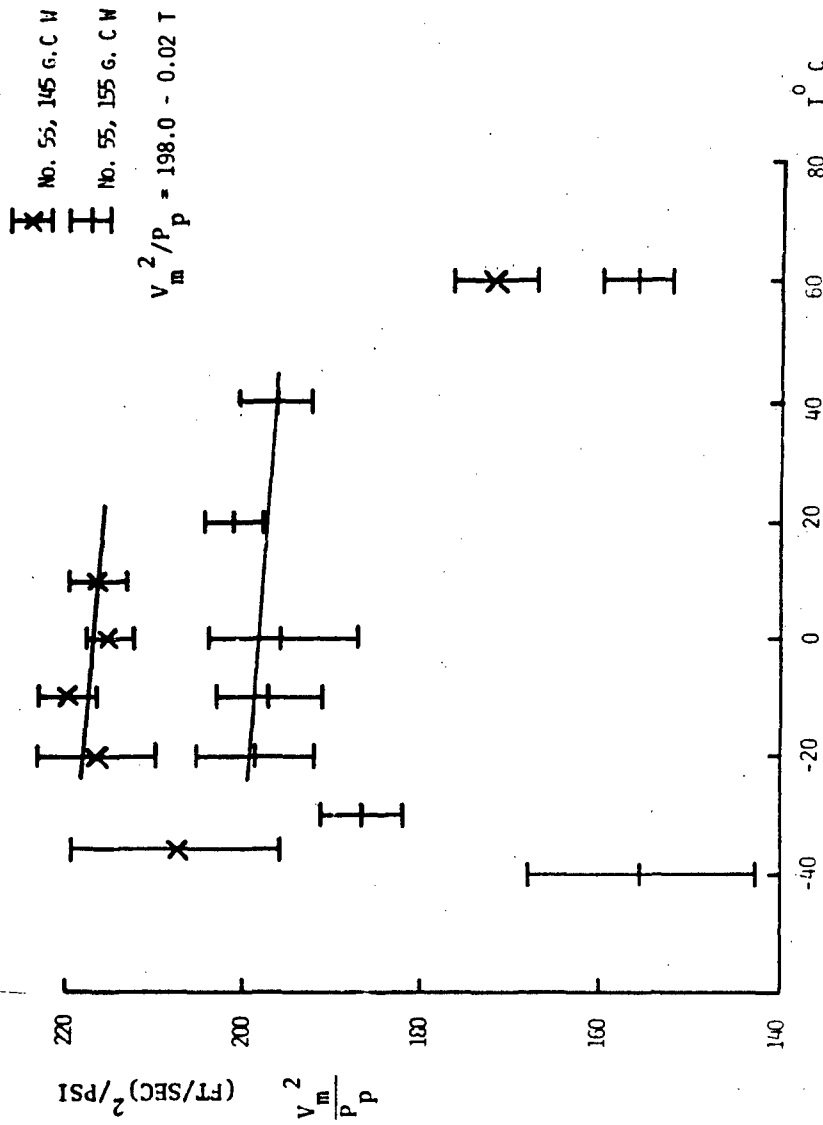


Figure 11. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant No. 55, 145- and 155-Gram Charge Weight

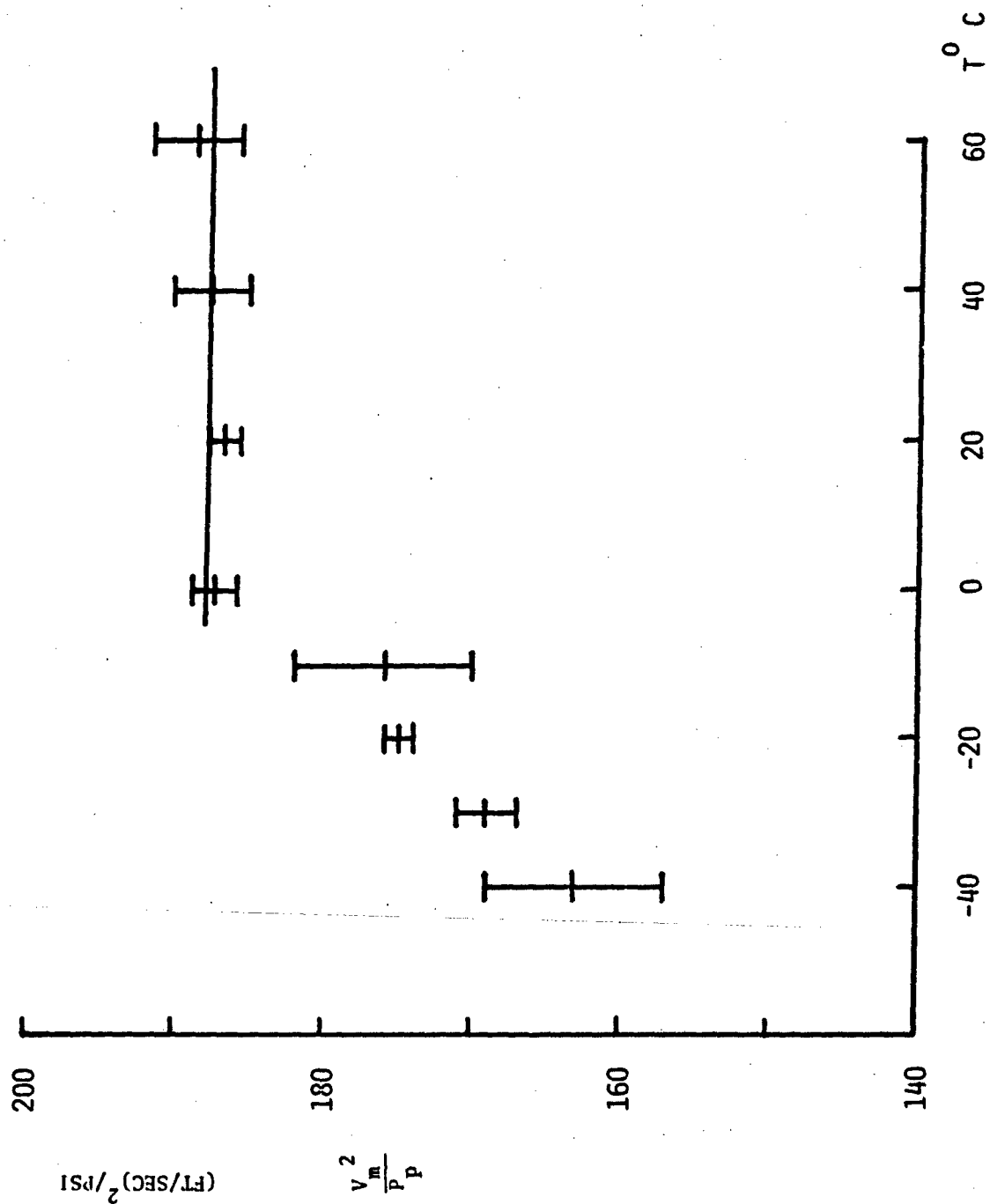


Figure 12. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant No. 13, 142-Gram Charge Weight

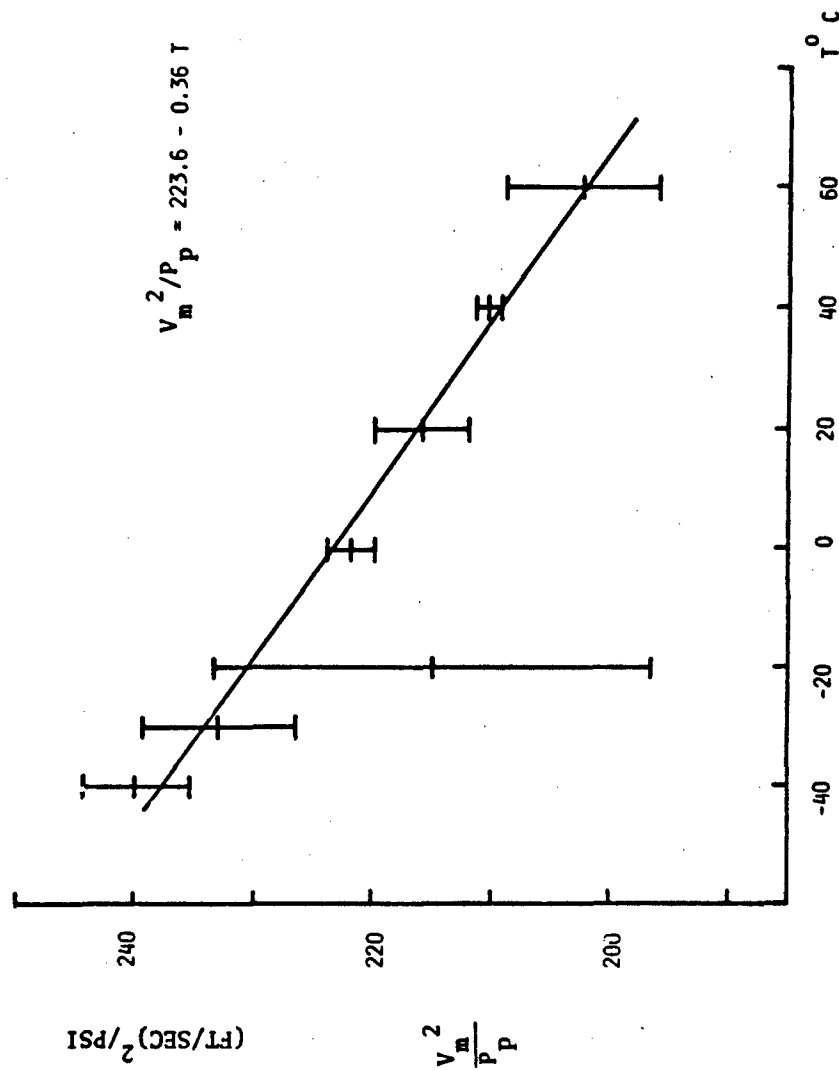


Figure 13. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant No. 34, 148-Gram Charge Weight

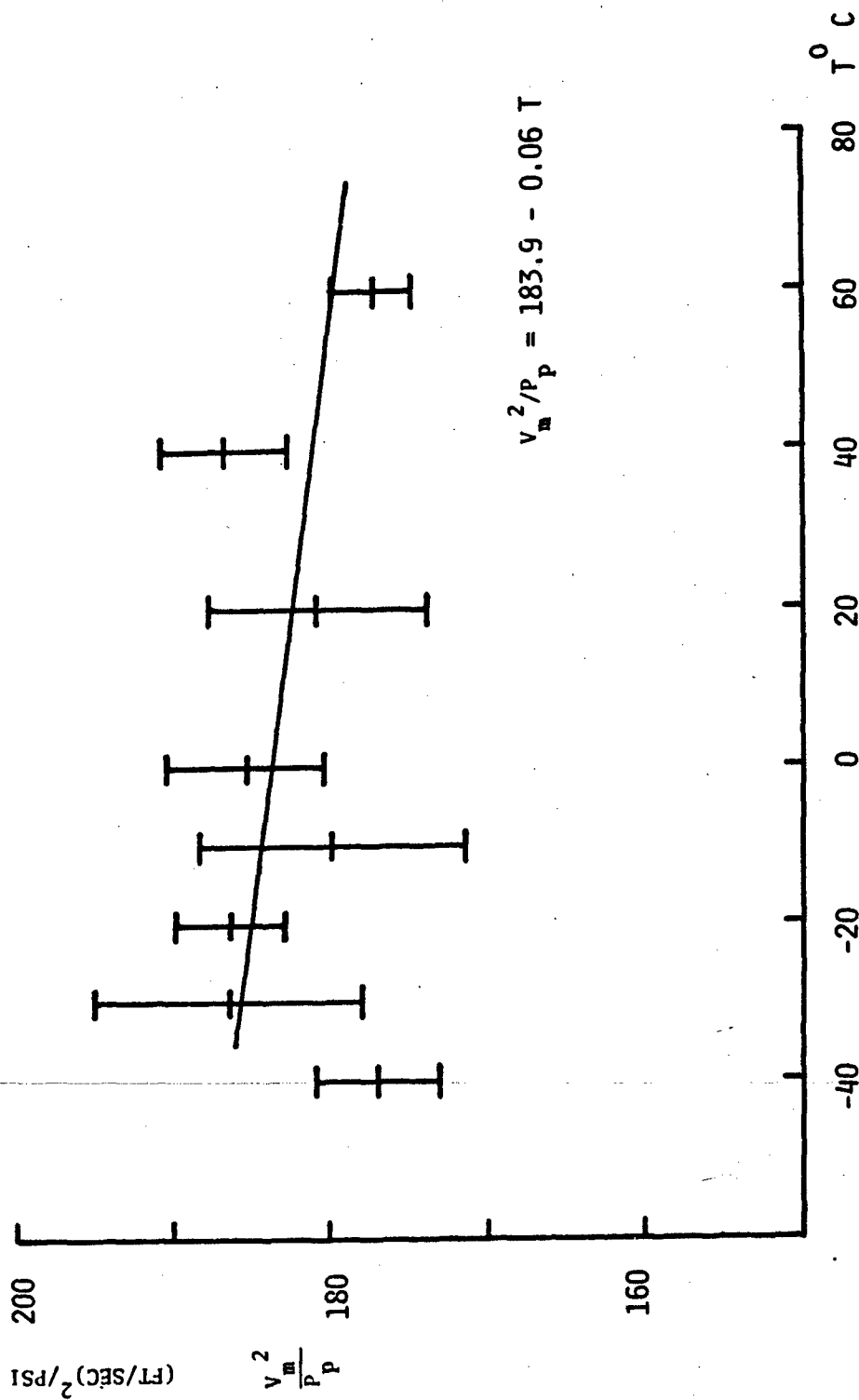


Figure 14. Muzzle Velocity²/Peak Pressure versus Temperature for the Triple Base Propellant M30 MOD, 155-Gram Charge Weight

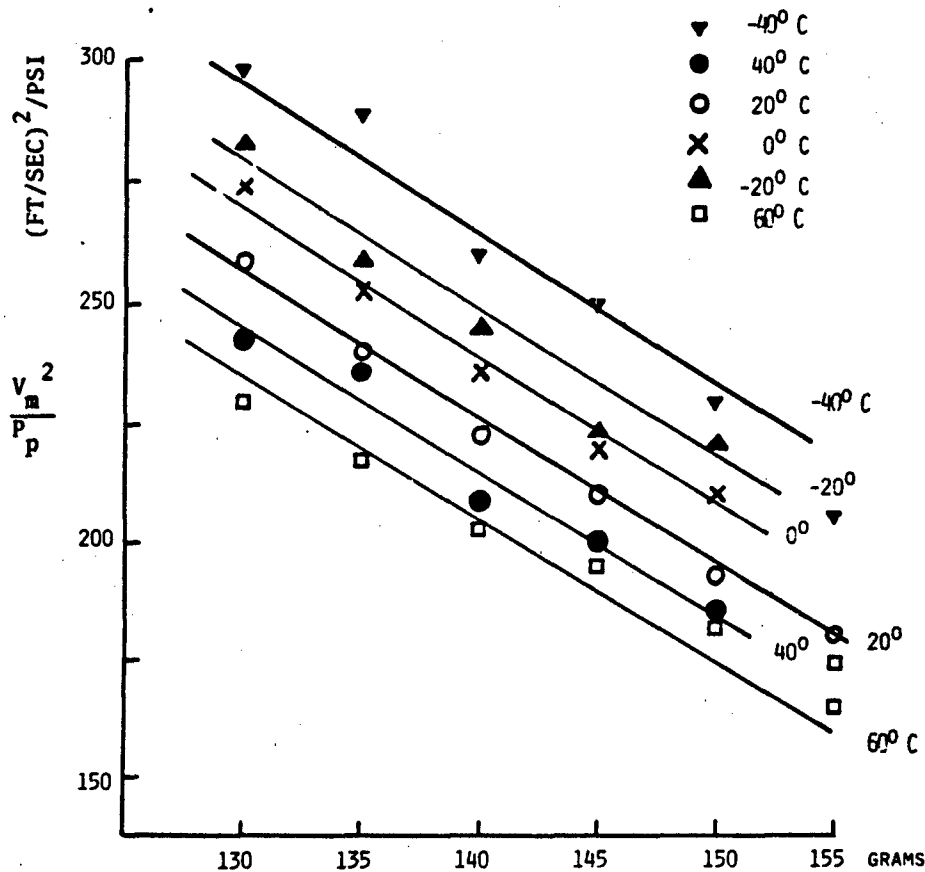


Figure 15. Muzzle Velocity²/Peak Pressure versus Charge Weight for the Double Base Propellant GAU-8 Extract

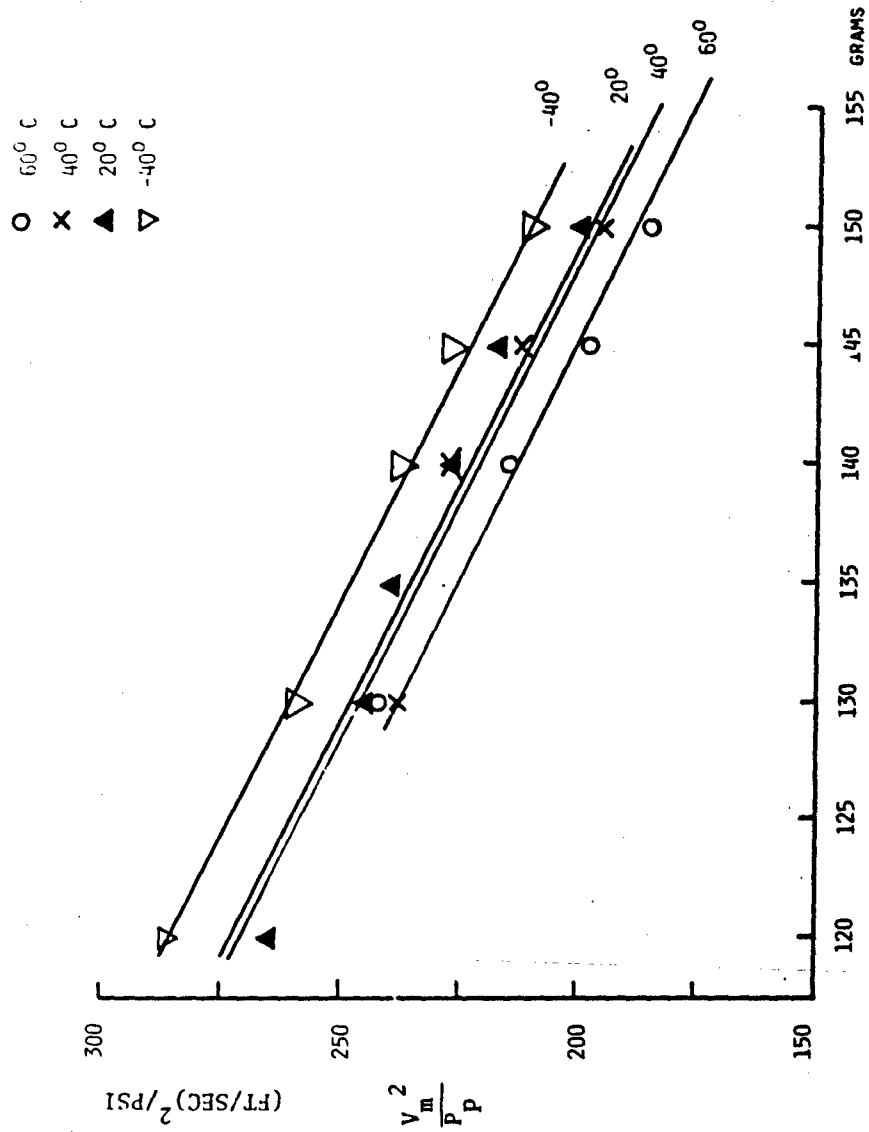


Figure 16. Muzzle Velocity²/Peak Pressure versus Charge Weight for the Nitramine Propellant IH .3

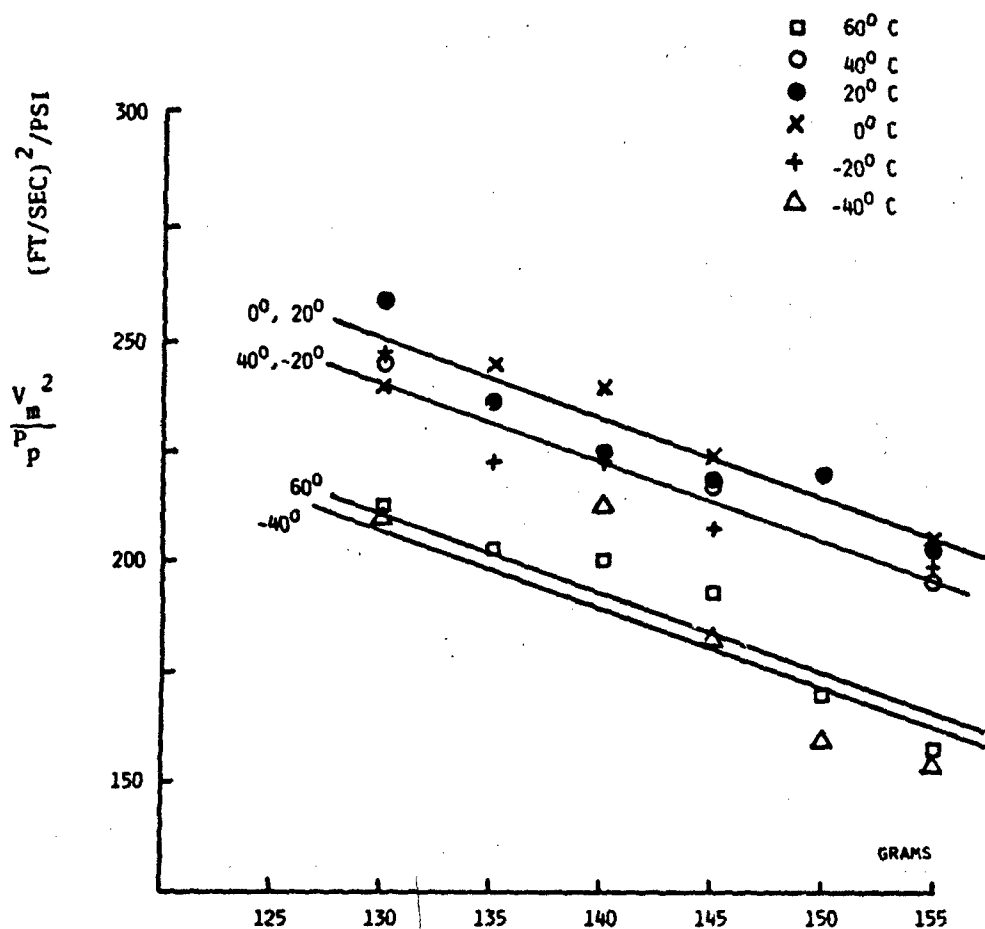


Figure 17. Muzzle Velocity²/Peak Pressure versus Charge Weight for the Triple Base Propellant No. 55

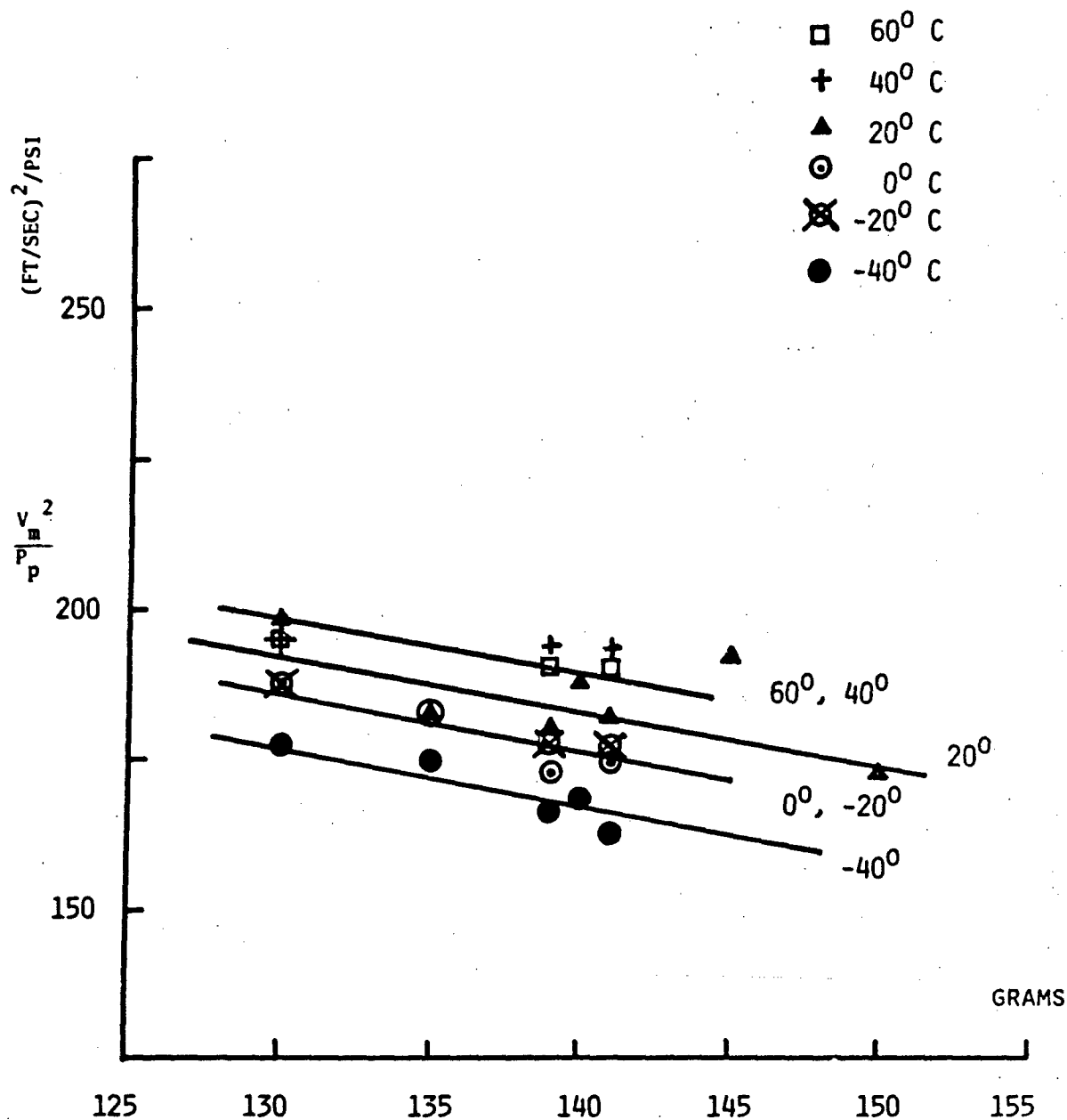


Figure 18. Muzzle Velocity²/Peak Pressure versus Charge Weight for the Triple Base Propellant No. 13

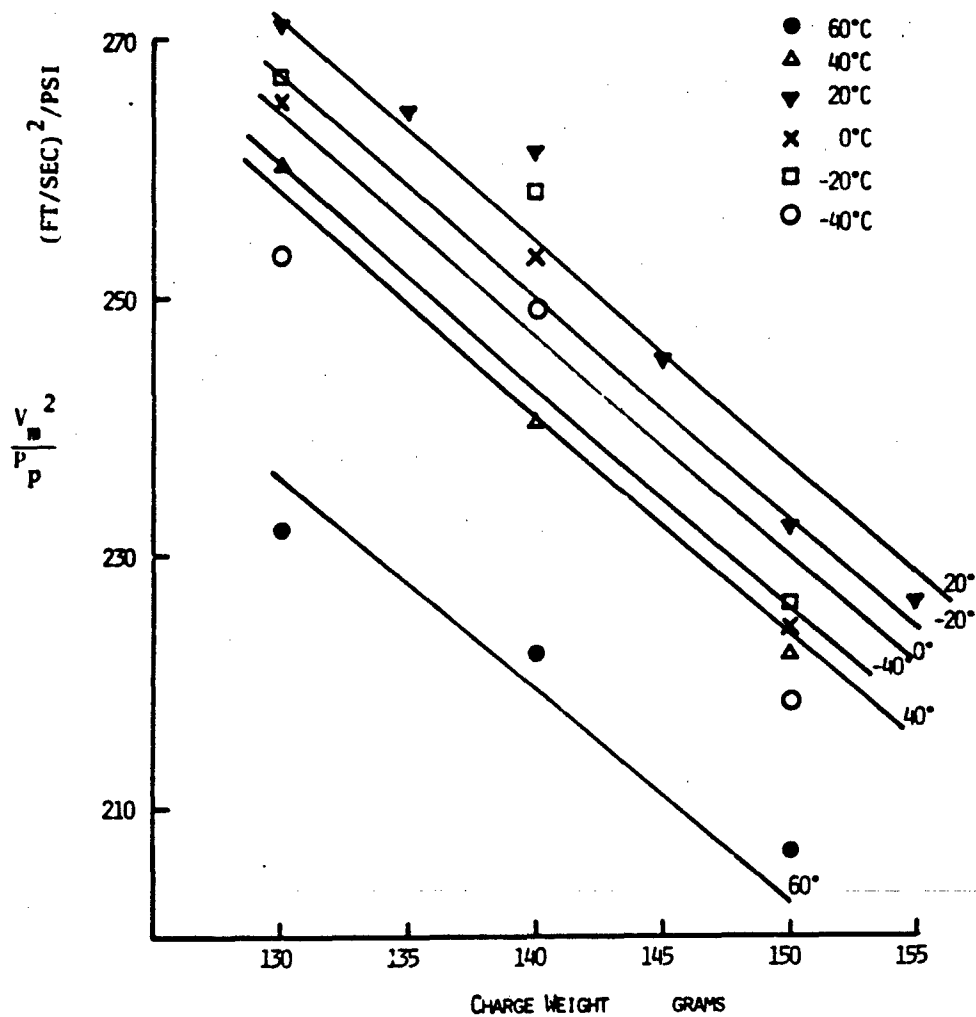


Figure 19. Muzzle Velocity²/Peak Pressure versus Charge Weight for the Triple Base Propellant No. 34

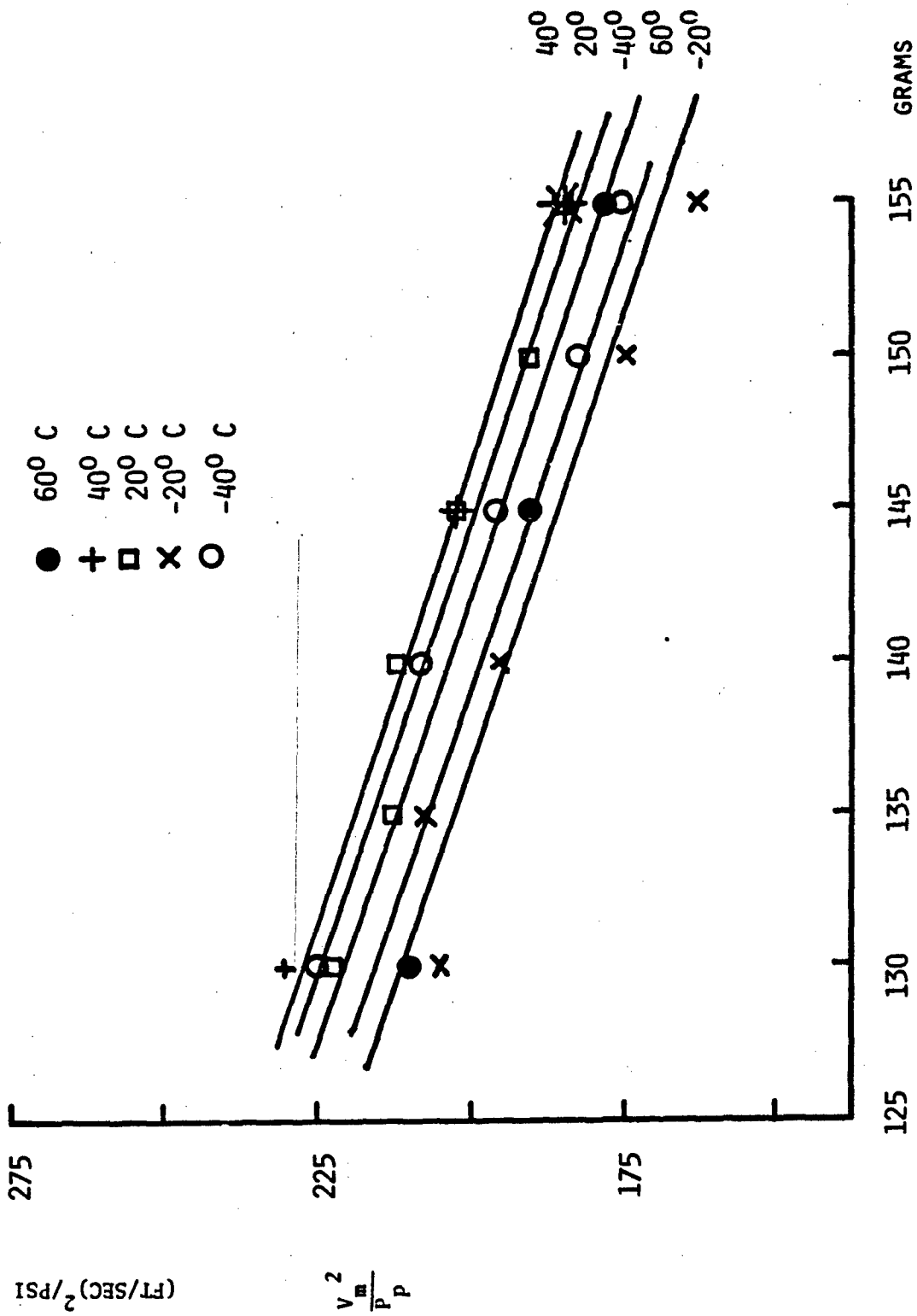


Figure 20. Muzzle Velocity²/Peak Pressure versus Charge Weight for M30 MOD Propellant

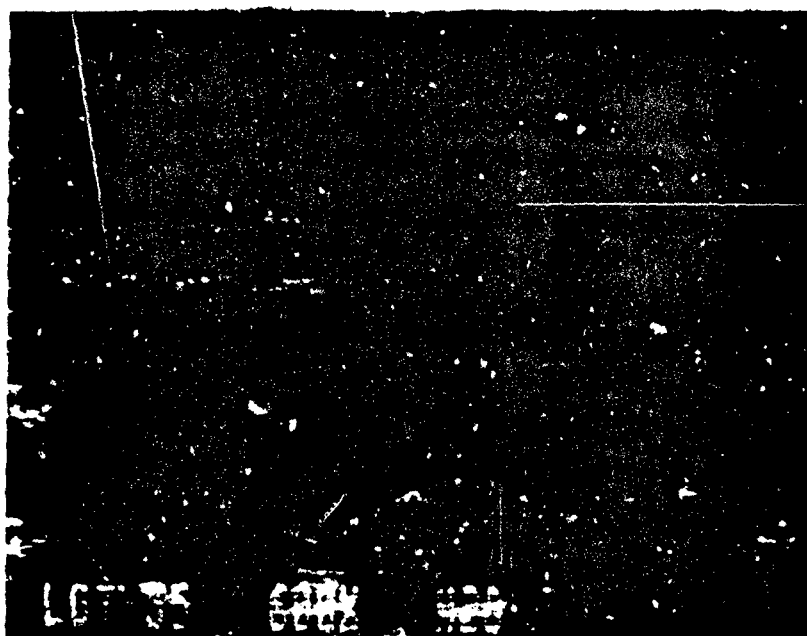
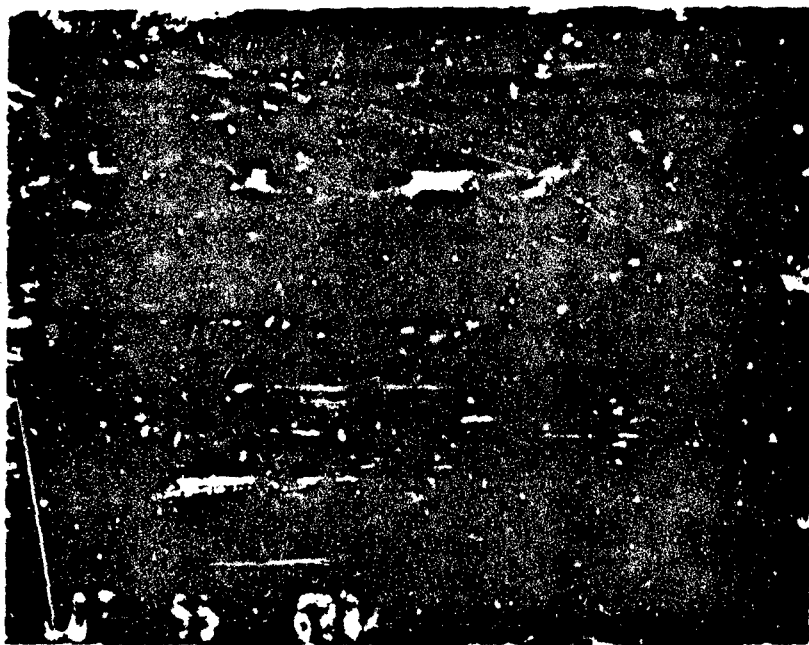


Figure 21. Scanning Electron Micrographs of the Fracture Surface of the Triple Base Propellant No. 55 (Magnification X600)

Bottom Micrograph Shows the Fracture Surface After the NQ has been Leached Out with Hot Water



Figure 22. Scanning Electron Micrographs of the Fracture Surface of the Triple Base Propellant No. 13 (Magnification X600)

Bottom Micrograph Shows the Fracture Surface After the NQ has been Leached Out with Hot Water

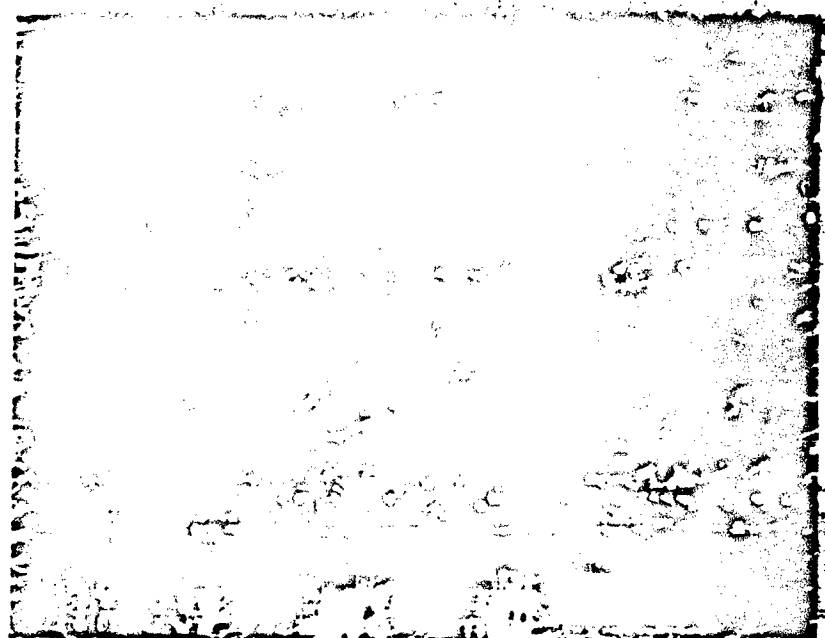
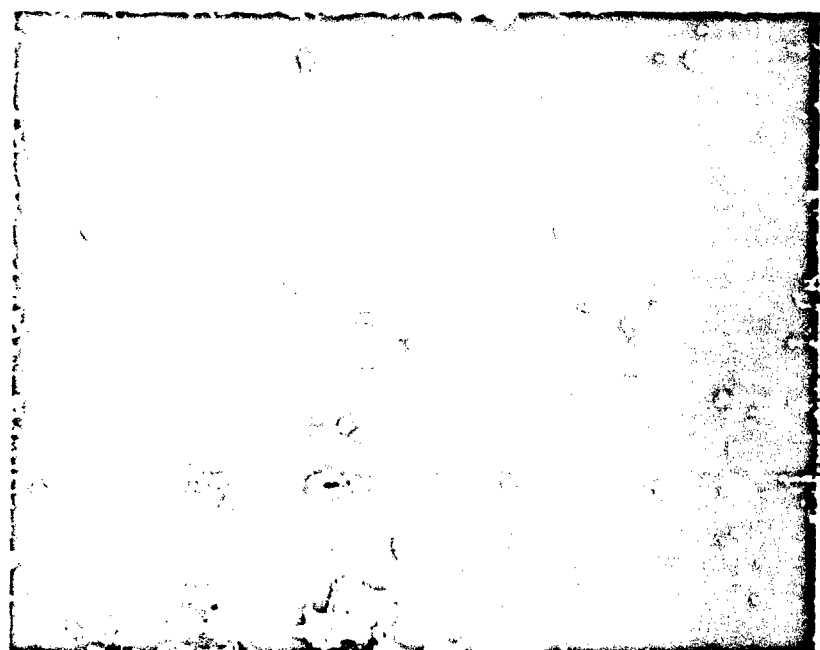


Figure 23. Scanning Electron Micrographs of the Fracture Surfaces of the Triple Base Propellant M30 MOD (Magnification X600)

Bottom Micrograph Shows the Fracture Surface After the NQ has been Leached Out with Hot Water

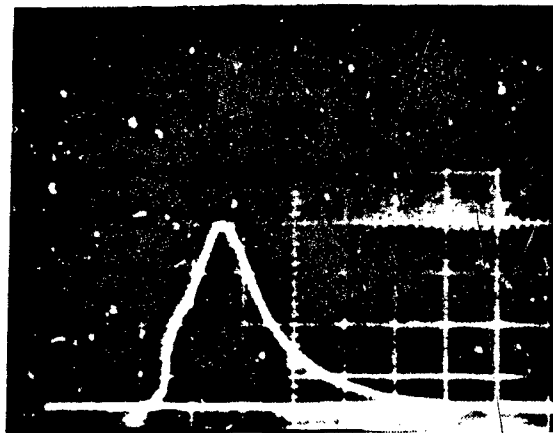
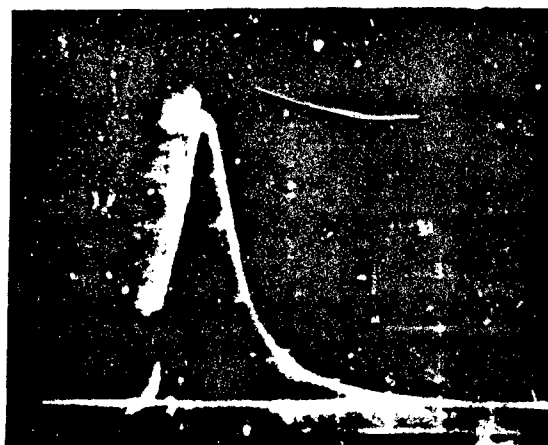
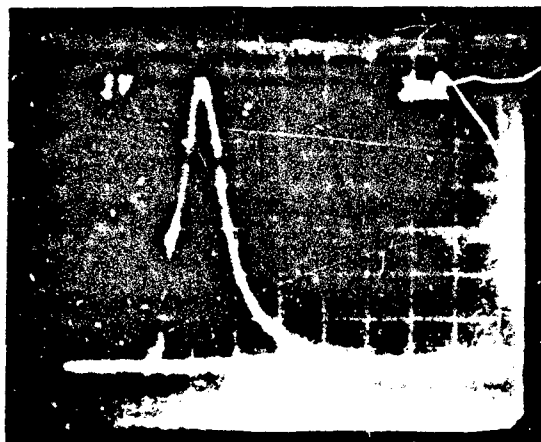


Figure 24. Pressure -- Time Traces for the
Single Base Propellant CIL 3331,
at 70°, 20°, and -40°C

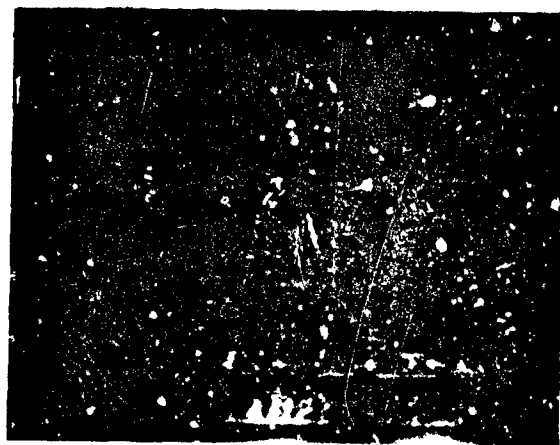
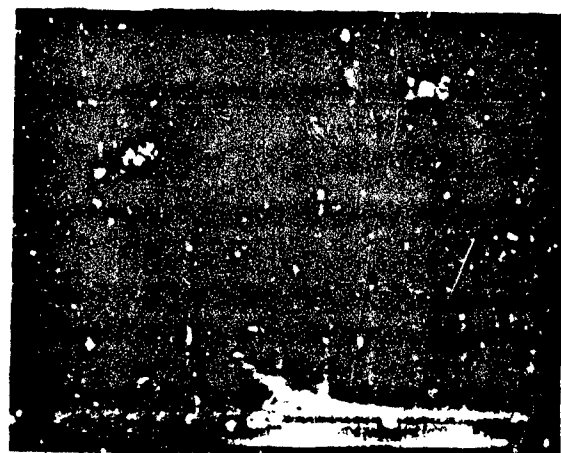
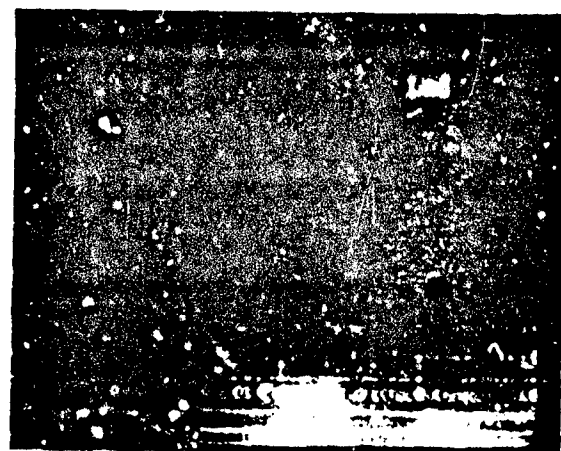


Figure 25. Pressure - Time Traces for the
Double Base Propellant GAU-8 Extract,
at 70°, 20°, and -40°C

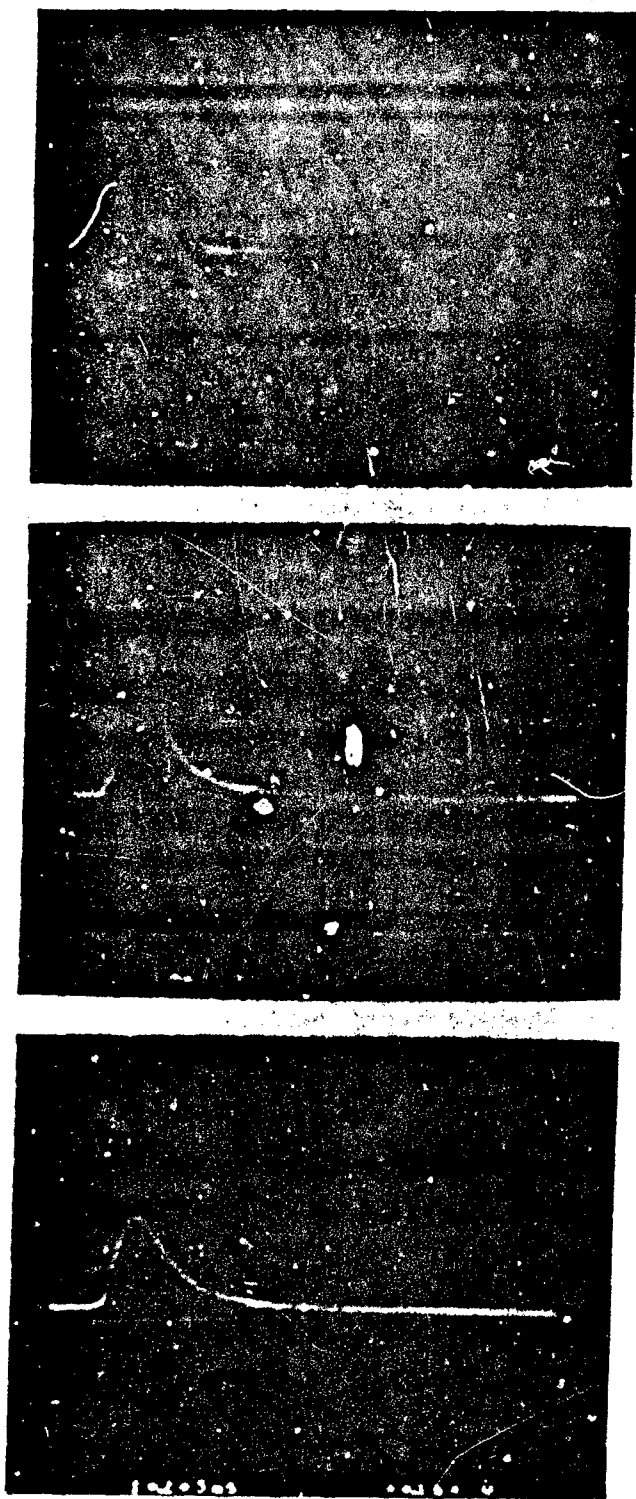


Figure 26. Pressure -- Time Traces for the
Nitramine Propellant, IH .3,
at 60°, 20°, and -40°C

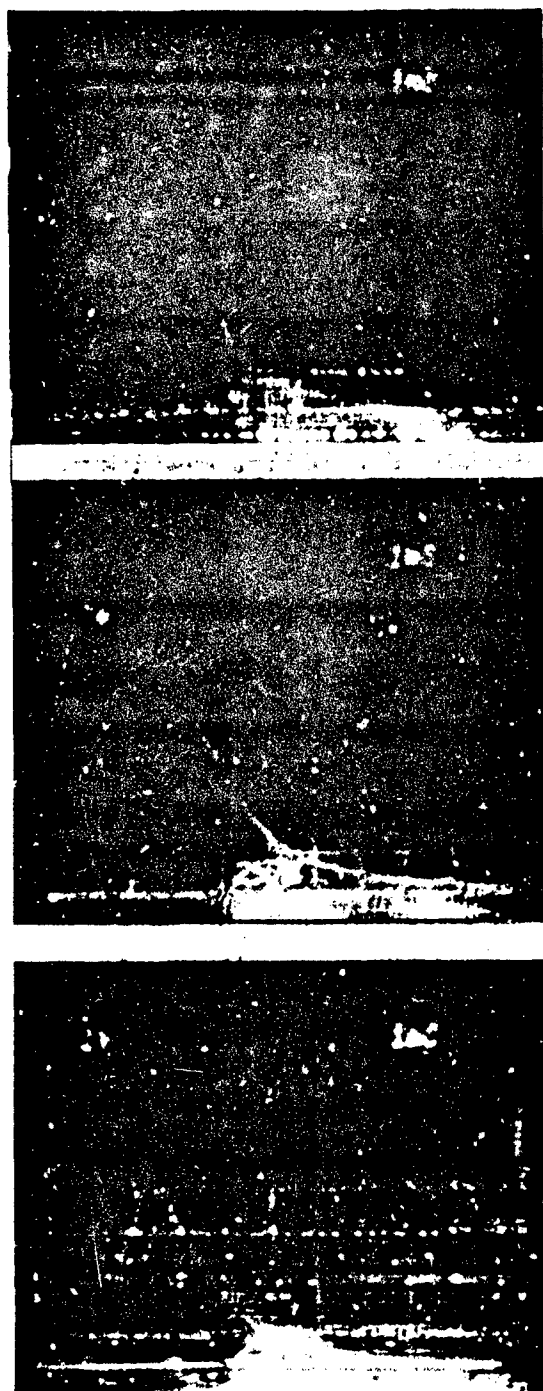


Figure 27. Pressure -- Time Traces for the
Triple Base Propellant No. 35,
at 60°, 20°, and -40°C

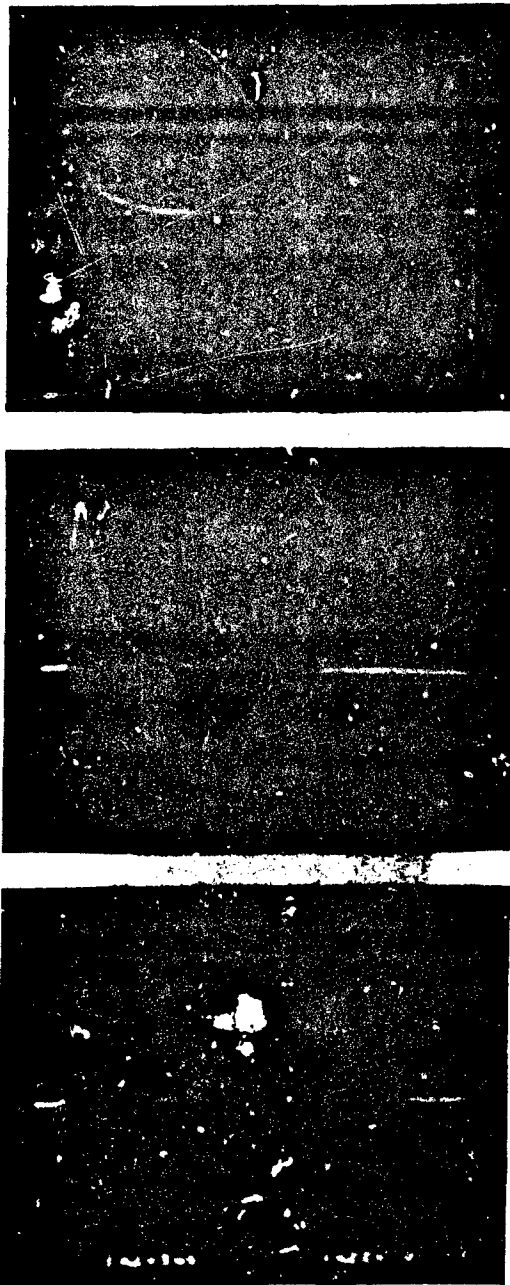


Figure 28. Pressure -- Time Traces for the
Triple Base Propellant M30 MOD,
at 60°, 20°, and -40°C